Biomechanical Studies on the Interrelation between Trunk Muscle Strength and Sports Performance

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Deutsche Zusammenfassung

In Mannschaftssportarten wie Fußball, Eishockey oder Basketball profitieren Sportler davon, dass der Körper hohe Belastungen bei Start und Stopp-Bewegungen, Richtungswechseln und Tacklings während des Wettkampfes toleriert. Ebenso werden in Individualsportarten, z.B. den leichtathletischen Disziplinen oder dem Skilanglauf, Höchstleistungen nur durch eine optimal trainierte und optimal angesteuerte Muskulatur ermöglicht. Die Kraft der Bauch- und Rückenmuskulatur wird dabei immer wieder als elementar beschrieben, da sie eine hohe Stabilität des Rumpfes bei Bewegung sicherstellen soll. So gilt die Stabilität des Rumpfes nicht nur als Grundlage einer hohen sportartspezifischen Leistungsfähigkeit, sondern soll auch zu reduzierten Rückenschmerzen, einem verringerten Verletzungsrisiko der unteren Extremität und allgemein zu weniger überlastungsbedingten Verletzungen führen. Daher wird im Sport eine beachtliche Zeitspanne des Trainings der Verbesserung der Rumpfkraft gewidmet und eine bedeutende Anzahl von Tests findet Anwendung, um die Kraft der Rumpfmuskulatur bei Athleten zu bewerten. Ziel dieses Vorgehens ist es, die Leistung der Athleten zu optimieren und Verletzungen vorzubeugen.

Das Ziel der vorliegenden Arbeit ist es, die Annahmen und bisherigen Erkenntnisse zum Stellenwert der Rumpfmuskulatur im Sport aus verschiedenen Blickwinkeln zu betrachten und aufgrund der durchgeführten Untersuchungen zu bewerten. Mittels einer Quantifizierung der Aktivität der Rumpfmuskulatur in unterschiedlichen Bewegungen werden genauere Aufschlüsse über ihre Bedeutung für das Leistungsvermögen angestrebt. Eine weitere wichtige methodologische Perspektive bietet hier die Betrachtung der Messmethoden zur Bestimmung der Kraft der Rumpfmuskulatur. Darüber hinaus wird nach einem Zugang gesucht, der zum besseren Verständnis der allgemeinen Bedeutung der Kraft der Rumpfmuskulatur für die sportliche Leistungsfähigkeit beiträgt. In den vier vorgestellten Studien dieser Dissertation werden dazu unterschiedliche Methoden eingesetzt. Elektromyographische Messungen zur Bestimmung und Analyse der Muskelaktivierung sowie unterschiedliche Methoden der Kraftmessung zur Differenzierung verschiedener Kraftqualitäten. Eine Differenzierung der Kraftqualitäten erleichtert die Darstellung unterschiedlicher Aspekte der Rumpfkraft wie z.B. Maximalkraft und

Kraftausdauer in Bezug auf wichtige sportlichen Leistungsparameter wie Sprint, Richtungswechselschnelligkeit oder Gleichgewicht. Die Kraftleistung der Bauch- und Rückenmuskulatur wird dazu mit Labor- und Feldmessmethoden in unterschiedlichen Bewegungen erfasst. Somit werden Aussagen zur Vergleichbarkeit und Verlässlichkeit der unterschiedlichen Messmethoden ermöglicht. Ebenso kann der Grad der Aktivität der Rumpfmuskulatur und der Einfluss der Rumpfkraft auf zentrale Leistungsparameter im Sport dargestellt werden.

In der ersten Studie wird ein in der Schweiz häufig verwendete Feldmessmethode (Bourbon-Test: Unterarmstütz, Seitstütz, modifizierter Sørensen-Test) mit einer Labormessmethode (isometrische Rumpfflexion, -extension, -lateralflexion, -rotation) in einer Gruppe von hochklassigen Fussballerinnen und Fussballern verglichen. Eine Vielzahl von Rumpfkrafttests finden in der Forschung nebeneinander Anwendung, aber der Zusammenhang und die Vergleichbarkeit der gemessenen Werte ist nicht bekannt. Ziel dieser Studie ist es deshalb, eine Differenzierung der Messmethoden hinsichtlich der Kraftleistungen zu ermöglichen. Es zeigt sich, dass maximal ein geringer Zusammenhang zwischen der Leistung in den Tests der Feldmessung (Zeit bis zum Abbruch der Tests) und den isometrischen maximalen Kraftmessungen besteht (Pearson's Korrelation: $-.14 < r < .36$). Die maximale Kraftleistung liefert somit keinen Hinweis auf die Kraftausdauerleistungsfähigkeit und umgekehrt. Somit können die Tests als komplementär bewertet werden. Hingegen, unterschieden sich erbrachten Leistungen in den Feldmessungen (Kraftausdauertests) zwischen Männern und Frauen nicht. Dabei ist die Muskelaktivität während der Kraftausdauerleistung sehr hoch und übertrifft 100% des willkürlichen isometrischen Muskelaktivitätsmaximums. Dieser Effekt ist bei Frauen stärker ausgeprägt als bei den Männern. Bei allen Kraftausdauertests kann eine kontinuierliche Zunahme der Muskelaktivität der Bauchmuskulatur über die Zeit festgestellt werden, was für eine zunehmende muskuläre Ermüdung spricht. Jedoch wurde in den Untersuchungen zu Unterarmstütz und Seitstütz hauptsächlich eine Ermüdung der oberen Extremitäten als Grund für den Testabbruch angegeben, während dies beim Sørensen-Test vornehmlich der Rumpf dafür verantwortlich gemacht wird. Der Test im Unterarmstütz wird in vielen Sportdisziplinen zur Diagnostik der Rumpfkraft verwendet, wobei die Validität des Tests zur Rumpfkraftbestimmung aufgrund des Abbruchkriteriums „Ermüdung der oberen Extremität“ hinterfragt werden sollte. Die hohe Aktivierung der beteiligten Muskulatur vor allem in der zweiten Hälfte der maximal möglichen Haltezeit rechtfertigt allerdings, wie sich zeigt, die Verwendung der Übungen in Kräftigungsprogrammen für die Rumpfmuskulatur.

In der zweiten Studie wurde die Reliabilität für unterschiedliche Bewegungsrichtungen des Rumpfes an einem isokinetischen Kraftmessgerät (IsoMed 2000) untersucht. 15 gesunde Sportstudenten wurden nach einer Gewöhnungsmessung an vier weiteren Messzeitpunkten im isometrischen und isokinetischen Modus (Bewegungsgeschwindigkeit 60°/s und 150°/s) für die Bewegungsrichtungen Rumpfflexion und –extension, und Rechts- und Linksrotation in ihrer maximalen Kraftleistung getestet. Als zuverlässigster Testmodus erwies sich die isokinetische Kraftmessung in der Bewegungsrichtung Rumpfflexion und –extension bei einer Geschwindigkeit von 60° pro Sekunde (ICC=0,92-0,96; 3,7% < CoV < 7,7%; 0,08 Nm/kg < SEM < 0,24 Nm/kg). Ebenso kann die Zuverlässigkeit der isometrischen und der isokinetischen Kraftmessung bei einer Bewegungsgeschwindigkeit von 150°/s wie auch für die übrigen Bewegungsrichtungen als gut bezeichnet werden. Dabei zeigte sich, dass Gewöhnungsmessungen grundsätzlich immer durchgeführt werden sollten, da die Reliabilitätswerte zwischen Gewöhnungsmessung und dem ersten Messtag tiefer lagen als zwischen den übrigen vier Messzeitpunkten.

Die dritte Studie untersuchte die Relevanz der Kraft der Rumpfmuskulatur für das sportliche Leistungsvermögen in der Ausprägung von Leistungsparametern wie Geradeaus-Sprint, Richtungswechselschnelligkeit und Gleichgewicht in einer dreiarmigen kontrolliert randomisierten Cross-Over-Studie mit 24 Sportstudierenden. Zwischen zwei Leistungstests (vorher/nachher) zur Erfassung der Sprint- und Richtungswechselschnelligkeit und des Gleichgewichts sowie der Kraft der Bein- und Rumpfmuskulatur wurde eine 20-minütige intensive Ermüdung entweder der Bein- oder der Rumpfmuskulatur oder eine Kontrollbedingung in Ruhe durchgeführt. Der Vergleich der Interventionsergebnisse zeigte, dass aus dem Ermüdungsprotokolls jeweils die Ermüdung der belasteten Körperregion resultierte, allerdings mit jeweils unterschiedlichen Auswirkungen. Aus der Rumpfmuskelermüdung resultierte eine Abnahme der Leistung der Richtungswechselschnelligkeit und des Gleichgewichts, ein Einfluss auf die Leistung im Geradeaus-Sprint konnte nicht festgestellt werden. Dagegen reduzierte die Beinermüdung, bis auf die Rumpfkraft, alle gemessenen Leistungsparameter deutlich stärker. Somit kann die Kraft der Rumpfmuskulatur als leistungsrelevant eingeschätzt werden, wenn das Gleichgewicht bzw. die Richtungswechselschnelligkeit in einer Sportart wichtig sind. Folglich ist ein Training der Rumpfmuskulatur für diese Sportarten empfehlenswert, wobei gilt, dass der Stellenwert der Kraft der Beinmuskulatur für die Mehrheit der untersuchten Leistungsparameter deutlich höher einzustufen ist.

In einer vierten Studie wurde untersucht, wie bei Kniebeugen mit der Langhantel (Back-Squat, Front-Squat, Overhead-Squat) die Rumpfmuskulatur aktiviert wird und sich dabei die Lordose der Lendenwirbelsäule verhält. Die Bewegung der Lendenlordose wurde erfasst, da die Bauchmuskulatur als mitverantwortlich für die Kontrolle der Lordose in der Lendenwirbelsäule gilt. Neben einer stabilen Ausgangsposition für die Kniebeuge mit beiden Füssen am Boden wurde in einer Variation die Standfläche nur auf den Vorfuss reduziert, so dass die Fersen keinen Bodenkontakt hatten. Mithilfe eines marker-basierten, dreidimensionalen Bewegungsanalyse-Systems (Qualysis, visual3D) und Kraftmessplatten wurde die Ausführung der Kniebeugen in den einzelnen Variationen aufgezeichnet. Aufgrund der Position ausgewählter Köpermarker konnten die Kniebeugen in drei Abschnitte unterteilt werden (Abwärtsbewegung, Umkehrpunkt, Aufwärtsbewegung). Elektromyographische Daten der Rumpfmuskulatur und der Schwankweg des Kraftangriffpunktes auf der Kraftmessplatte wurden analysiert. Während eine Variation der Art der Kniebeuge die Aktivität der Rumpfmuskulatur änderte, konnte dieser Unterschied durch Reduktion der Standfläche auf den Vorfuss in der gleichen Variante nicht beobachtet werden. Somit ist die Wirkung einer Reduktion der Standfläche für die Aktivität der Rumpfmuskeln als nur gering einzuschätzen.

Zusammen genommen liefern die Resultate der durchgeführten Studien wichtige Hinweise zum Stellenwert der Rumpfmuskulatur im Breiten- und Leistungssport. Insgesamt deuten die Ergebnisse der Untersuchungen darauf hin, dass die Kraft der Rumpfmuskulatur die sportliche Leistungsfähigkeit beeinflusst. So zeigte sich, dass die Ermüdung der Rumpfmuskulatur zu einer reduzierten Leistung bei Richtungswechsel- und Gleichgewichtsaufgaben führte. Somit erscheint der weitverbreitete Einsatz von Rumpfkraftübungen und auch der Gebrauch von Tests zur Bestimmung der Rumpfkraft gerechtfertigt. Die Validität des in der Sportpraxis häufig eingesetzten Unterarmstützes ist jedoch zu hinterfragen, da dieser meist aufgrund der Ermüdung der oberen Extremität und nicht wegen einer Ermüdung der Rumpfmuskulatur abgebrochen wird. Ein Einsatz alternativer Messmethoden zur Bestimmung der Rumpfkraft wird daher empfohlen. Eine belastbare Labormessung kann hierbei mittels einer isokinetischen Rumpfkraftmessung erfolgen. Zur Leistungsverbesserung der Rumpfkraft werden verschiedene Trainingsinhalte empfohlen, die auch Squats beinhalten sollten. Anhand der elektromyographischen Daten bei verschiedenen Arten von Squats kann geschlossen werden, dass die Rückenmuskulatur und der externe schräge Bauchmuskel am stärksten beansprucht werden. Die Variation der Art des Squats (back squat>fronts squat>overhead squat) geht mit einer Zunahme in der Rumpfmuskelaktivität einher. Hingegen bewirkte die Reduktion der Standfläche in der gleichen Übung keinen Unterschied in der Aktivierung der Rumpfmuskeln.

Rumpfkraft ist relevant für die sportliche Leistung. Ein Training der Rumpfkraft kann daher als eine sinnvolle Ergänzung des Krafttrainings angesehen werden. Unterschiedliche Arten von Squats sowie andere Varianten wie Unterarmstütz können dazu miteinbezogen werden. Unklar bleibt, wie die beste Methode zur Bestimmung der Rumpfkraft aussehen könnte. Insgesamt und im Vergleich sollte der Stellenwert der Rumpfmuskulatur relativiert werden, da die Relevanz der Beinmuskulatur für die sportliche Leistungsfähigkeit als höher eingeordnet werden kann.

Summary

In team sports such as football, ice hockey or basketball, athletes benefit from the body's ability to tolerate high loads during start and stop movements, changes of direction, and tackles during competition. Likewise, in individual sports, such as track-and field or cross-country skiing, maximum performance is only possible with optimally trained and optimally controlled muscles. The strength of the abdominal and back muscles is widely considered crucial, as it is responsible for a high stability of the trunk during movement. The stability of the trunk is not only considered the basis of a high performance in specific sports discipline, but can also contribute to reduced back pain and risk of injuries to the lower extremities and, in general, to fewer overuse injuries. Therefore, a considerable amount of time in training is devoted in order to improve trunk strength in sports. A considerable number of tests, then, is typically applied in order to evaluate trunk muscle strength in athletes. But, surprisingly, the relevance and comparability of the measured values are poorly understood. Therefore, this study on some central aspects of the interrelation of trunk muscle strength and sports performance sets out to highlight the contribution made to the improvement of the athletes' performance in a wide range of sports and to the prevention of sports injuries.

This thesis seeks to critically access the methodological presumptions which underlie and have guided the existing scholarship, and the experimental research, on the role of trunk muscles in sports. It will do so by using different methodological perspectives in its discussion and by making use of a set of new investigations and tests. In particular, the quantification of the activity of the trunk muscles in different movements will be discussed as well as measurements which try to determine the strength of the trunk muscles. Finally, this study aspires to contribute to a better overall understanding of the interrelation of trunk muscle strength and athletic performance on the one hand and to preventive training on the other hand.

In four studies presented in this thesis, different methodological approaches are used to that end: electromyographic measurements for the determination and analysis of muscle activation as well as different methods of strength assessment for the differentiation of various strength qualities. The differentiation of the strength qualities allows the description of various aspects of trunk strength, such as maximum strength and strength endurance, which relate to essential athletic performance parameters such as sprint, change of direction or balance. The performance in the strength of the abdominal and back muscles is measured with laboratory and field methods in different movements. The findings are not only used to re-address the discussions on the comparability and reliability of different measuring methods but also seek to advance our understanding of the degree of activity of trunk muscles and the influence of trunk strength on basic performance parameters in sport.

In the first study, a field test method which is frequently used in Switzerland (Bourbon test: prone plank, side plank, Sorensen test) is compared with a laboratory procedure (isometric trunk flexion, extension, lateral flexion, rotation test) in a group of high-level soccer players. This study aims to compare different assessment methods. No relevant correlation between the performance in the field test (time to failure) and the maximum isometric force measurements (Pearson's correlation: $-.14 < r < .36$) is observed. The maximum force output, therefore, does not indicate the strength endurance performance and vice versa. The performances in the field measurements do not differ between men and women. Muscle activity during strength endurance performance, however, is very high and exceeds 100% of maximum voluntary isometric muscle activation. This effect is more pronounced among female athletes than males. All strength endurance tests show a continuous increase in abdominal muscle activity over time, indicating muscular fatigue. However, in the prone plank and side plank test the upper extremities are mentioned as the main reason for the test termination, whereas in the Sørensen test it is the trunk. The prone plank test is frequently used in sports to assess trunk strength but, as the discussion of the results demonstrate, the validity of the test to determine trunk strength should be questioned. However, the high activation of the muscles involved, especially in the second half of the maximum performance time, justifies the use of the exercises in strengthening programs for the trunk muscles.

In the second study, the reliability for different movement directions of the trunk was investigated on an isokinetic force measuring device (IsoMed 2000). Fifteen healthy sports students were tested in an isometric and isokinetic mode (movement speed 60°/s and 150°/s) for the movement directions trunk flexion and extension, as well as right and left rotation. Maximum trunk strength was evaluated during five test days, including a familiarization test. The most reliable test mode was the isokinetic force measurement of trunk flexion and extension at a speed of 60° per second (ICC=0.92-0.96; 3.7% < CoV < 7.7%; 0.08 Nm/kg < SEM < 0.24 Nm/kg). The reliability of the isometric and isokinetic strength measurement at 150°/s as well as the other directions of motion can also be described as sufficient. However, familiarization tests should always be performed as the reliability between the familiarization measurement and the first day of measurement was lower than between the other four tests.

In the third study, the relevance of trunk muscle strength for athletic performance was investigated in a three-armed randomized controlled cross-over study with 24 sports students in which parameters such as a linear sprint, agility and balance were evaluated. A fatiguing 20-minutes workout aiming either to fatigue leg or trunk muscles or for control condition 20 min of rest were performed. Before and after the fatigue protocol or control condition, sprint, agility, and balance performance as well as leg and trunk muscle strength were assessed. The fatigue protocol resulted in fatigue of the respective body region. Trunk muscle fatigue resulted in a decrease in change of direction sprint and balance performance but had no affect linear sprint speed. Leg fatigue impaired, except for trunk strength, all performance parameters to a greater extent in comparison to trunk fatigue. Thus, trunk muscle strength can be regarded as relevant for selected physical performance components. Consequently, training of the trunk muscles can be recommended in sports where the speed of directional changes and balance are relevant. However, the importance of leg strength for sports performance can be rated higher.

Finally, the fourth study investigated the activation of trunk muscles as well as the deformation of the lumbar spine during a popular strength exercise such as barbell squats (back squat, front squat, overhead squat). Two standing conditions were defined (I) one with both feet on the ground and (II) one with a reduced base of support standing only on the forefoot without ground contact of the heels. Since the abdominal muscles are considered responsible for controlling the lordosis in the lumbar spine, the lordosis movement was also tracked. For this purpose, a marker-based, three-dimensional motion analysis system (Qualysis, visual3D) and force plates were used to record the different squat variations. Based on joint angles and body markers, the squat movement was divided into three segments (a lowering, turning, raising phase) and the electromyographic data of the trunk muscles and the sway path of the center of pressure on the force plate were analyzed. While the activity of the trunk muscles differed between squat types, there was no relevant effect of the standing condition on muscle activity.

To sum up, the findings of this thesis seek to contribute to a better understanding of the relevance and function of trunk muscle strength in athletic performance. The results presented here provide relevant findings for recreational and competitive sports and strengthen the conclusion that trunk muscle strength substantially affects athletic performance. Therefore, the application of tests to determine trunk strength, is reasonable in various settings. However, the validity of the prone plank test which is frequently applied in sports practice must be questioned, since it is usually terminated due to fatigue of the upper extremities and not due to fatigue of the trunk muscles. The use of alternative measurement methods to determine trunk strength therefore is recommended here. Isokinetic trunk strength assessment is a reliable laboratory test procedure. Various training interventions are frequently recommended in order to improve trunk strength, often involving squat exercises. The variation of the squat type caused more considerable differences in trunk muscle activity compared to a reduction in the base of support. Therefore, variations of barbell squats could be promising alternatives in the engagement of trunk muscles. Trunk strength training can be an essential supplement in strength training. Overall, however, the contribution of leg muscles to athletic sprint and balance performance can be considered more relevant.

Introduction

Core training has become a part of the overall conditioning program for the vast majority of competitive athletes, irrespective of sport disciplines.[51; 116] Adequately developed trunk strength is widely regarded as an essential prerequisite for sports performance.[19; 63; 101] Therefore, a considerable amount of time is dedicated to training and improving trunk strength[25] and a remarkable number of tests have been developed are proposed[26; 32; 60] in order to evaluate the strength of trunk muscles in athletes.

Particularly in team sports such as soccer, ice hockey or basketball, athletes stand to benefit from tolerating high impacts on the trunk at starts and stops, changes in direction and tackles during competition. In individual sports like athletics[98] or cross-country skiing,[97] high performance is also attributed to the appropriate performance of the trunk muscles. High stability of the trunk during functional movements , therefore, is argued to be an essential determinant of sports performance.[64] Aside of performance, some evidence seems to suggest that higher trunk strength can lead to reduced back pain,[10; 55] decreased risk for the lower extremity[115; 117] and overuse injuries.[45] Core strengthening is therefore an integral part of athletic training but also in rehabilitation[1] and prevention programs.[95] However, there still is considerable controversy about its exact and relative importance, despite considerable efforts from sports practice as well as sport and physical therapists, who support the scientific findings mentioned above. In their review article about core stability training on sports performance measures, Reed et al. conclude:[92]

> *"Targeted core stability training provides marginal benefits to athletic performance. Conflicting findings and the lack of a standardization for measurement of outcomes and training focused to improve core strength and stability pose difficulties. Because of this, further research targeted to determine this relationship is necessary to better understand how core strength and stability affect athletic performance." (p. 2)*

Such an assessment, however, is critically limited because key terms like "trunk strength", "core strength", and "core stability" are often used interchangeably. To date for instance, there is no consensual definition of core performance.[2; 23] Since the content of the term is not uniformly defined, the measured parameters are often mixed in an almost arbitrary manner.[68] Therefore, in this thesis, the type of terminology of the respective authors are preserved, even if it partly does not reflect the measured parameter; e.g., the term "core stability" is used, even though strength endurance performance was measured. In a recent meta-analysis, strength endurance and maximum strength of the trunk are both summarized as indicators of trunk performance in the same category. As maximum strength and strength endurance represent very different aspects of performance, these two parameters, it is argued here, should not be summarized into one category of trunk performance. In the mentioned systematic review, the estimates of trunk performance were linked to sprint, 1 RM, or balance performance.[90] Such an analysis does not allow a precise and differentiated consideration of the cause-effect relationship between musculature and athletic performance.[51]

This example illustrates that the scientific evidence for the effectiveness of trunk training is still in its early stages. Nevertheless, the issue of core stability or core strength very much represents a central theme, both in research and training. A Google search on “Core stability” or “Core strength” on March 02, 2019 yielded more than 350 million or 705 million results in 0.3 s, respectively. The numerous contributions to the topic are manifold. The frequent occurrence of back problems in the general population generates a wide range of solutions being offered. The aesthetical desire for an attractive appearance and the promise of increased performance through well-trained trunk muscles stimulate the offer.

Looking back on earlier studies it becomes clear that traditionally concrete statements about the function of the spine[15] or performance of the trunk muscles[14] were provided. In recent studies, the topic is becoming more and more incoherent, with the descriptive functions and their importance becoming less conclusively. One reason for this might be caused by the fact that the research approaches have become more and more diverse. Measured dimensions (maximum strength, strength endurance, muscle activity, core stability) and the associated statements on increased performance, mobility, quality of life, freedom from pain, etc. seem to provide at times arbitrary parameters. And both their presentation and interpretation often appear to depend on the overall argument they aspire to promote.[68; 82; 107]

Anatomically speaking, the trunk serves as the center of every kinetic chain,[23] particularly in activities of daily life but also in sports movements. Exercises are fundamentally influenced by and dependent on trunk muscles. The benefit of training programs for trunk muscles to reduce back pain[69] and injuries[12], by and large, has become generally accepted, even though the underlying mechanisms are not completely understood.[50; 55] Meanwhile, sports performance also tends to benefit from an optimally developed neuromuscular performance of trunk muscles. Several studies have highlighted the positive aspects of additional trunk training on sports performance in various disciplines.[95; 99; 100] However, to date, there is limited evidence that trunk strength or optimal coordination of the trunk muscles can predict or even accurately assess an athlete's performance. Still, there is an obvious need for research to disentangle the relationship between trunk strength and sports performance.[53; 85]

This cumulative thesis, therefore, aims to shed light on the essential research questions of “how to measure trunk performance”, “is trunk strength linked to sports performance”, and “how do different training exercises affect the recruitment of trunk muscles”. The next sections first explain the basics of trunk strength (anatomy, definition, assessment methods). Subsequently, background information on assumptions and results in various areas of research (sports performance, injury prevention, rehabilitation) is presented. The approaches in the following own studies are based on these understandings.

Trunk – Core – Upper Body

Despite different views about which body parts belong to the trunk, whether hip and leg muscles, or the shoulder girdle are part of it,[1] the anatomical definition is quite clear. The trunk or, equally core or what in art is known as torso (*Figure 1*), covers the area from the pelvis to the thorax including the spinal column and is also referred to as upper body.[72]

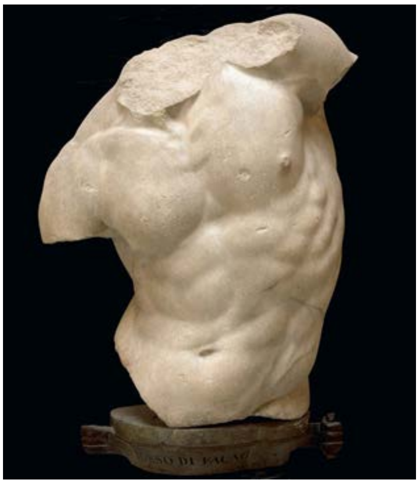

Figure 1: The human torso in art displaying the trunk as area from pelvis to thorax. (https://www.uffizi.it/en/artworks/torso-of-a-centaur)

The spine, its backbone, is the bony, articulated and mobile support of the trunk.[113] Cartilaginous connections between the vertebral bodies (intervertebral discs) and facet joints between the joint processes enable the mobility of the spinal column.[113] The vertebral arches with the articular and spinous processes determine the directions of movement. The spine moves in three directions: around a transverse axis (flexion and extension), around a sagittal axis (lateral flexion), and the longitudinal axis (rotation).[113] The movements of the spine are partly limited by the ribs, which also serve as origin and insertion for muscles belonging to the trunk.[113] The second important origin and insertion of trunk musculature is the distal end of the trunk, the pelvis.[15]

Muscles of the trunk

Aside of the passive structures, bones, discs, ligaments and joint capsules, multiple muscles and their connective tissues are mainly responsible for the movement and function of the trunk. When it comes to trunk strength, following the definition provided by the Canadian society for exercise physiology,[11] the following muscles are the focus of investigations: the internal and external oblique, the rectus abdominis and the erector spinae group. They are identified as the primary muscles to stabilize or move the trunk or spine, respectively.

The abdominal musculature consists of four muscles overall, divided into three layers: an inner layer (transverse abdominus), a middle layer (internal obliques) and an outer layer (external obliques). The aponeuroses of these muscles run in front of or behind the two strands of the fourth muscle, the rectus abdominis, and cross each other in the alba line.[91] Surrounded by the aponeurosis of the muscle layers, the rectus abdominis runs straight from the pubic bone to the 5th to 7th rib.

The four muscles stretch between the pubic bone, iliac crest, inguinal ligament, and ribs, while the aponeuroses of these muscles connect on the back with the thoracolumbar fascia. Together, these muscles form a solid shell that protects the intestines and supports an upright posture as well as the spinal movements.[91] In addition, the muscles' contraction supports breathing and increases intra-abdominal pressure which is a functional prerequisite during sneezing, coughing, lifting or childbirth.[113]

Muscles of the back are pooled under the term erector spinae They are organized into a medial (deep or local), and a lateral (or global) tract (Table 1).[43; 91] The deep, local musculature comprises muscles that attach directly to the vertebral bodies and origin from the pelvis (sacrum). The semispinalis, intertransversarii, rotatores, and multifidius muscles are regarded as representatives of this group.[22; 23; 43] Bergmark describes the multifidius muscles also as an additional stabilizer of the lumbar lordosis (MF, Figure 2B).[15] Hence, the intertransversii muscles provide increased stiffness and eventually mechanical stability to the spine despite their comparatively small muscle force, due to their short length.[15; 43; 91] The deeper the muscles are located, the shorter they are, and the fewer vertebral bodies are interconnected by them, typically only one to two.[61] In contrast, the global musculature is characterized by their skipping of several vertebral segments and their partial attachment to the ribs. These muscles are also responsible for changing the position of the thorax in relation to the pelvis (ESg, Figure 2A). Representatives of this group are known as longissimus and iliocostalis.[22; 43]

Both groups have a connection to the thoracolumbar fascia, which is anatomically divided into three layers, enclosing the back muscles.[15] Bogduk meticulously describes the sophisticated anatomical course of the lumbar back muscles.[22] All three layers of the thoracolumbar fascia come together and build the aponeurotic origin of the transverse abdominis muscle. The back muscles and the abdominal wall connect here to form a hull, thus creating the trunk muscles.

Table 1: Muscles of the lumbar spine, subdivided into a global (lateral) and a local (medial or deep) muscle group modified according to Akuthato[2] (2004, p.87)

Global Muscles (dynamic, phasic, torque producing)	Local Muscles (postural, tonic, segmental stabilizers)
Rectus abdominis	Multifidii
External oblique	Psoas major
Internal oblique (anterior fibers)	Transversus abdominis
Iliocostalis (thoracic portion)	Quadratus lumborum
	Diaphragm
	Internal oblique (posterior fibers)
	Iliocostalis and longissimus (only lumbar portions)

It is noteworthy that muscles like the psoas and latissimus dorsi muscles indirectly produce an influence on the stability of the lumbar back. The spinal system must be able to maintain stability despite action in these two muscle groups.[15] Both muscle groups work in synergy with the erector spinae in the lumbar spine.

Likewise, the hip muscles, especially the gluteus muscles, work on the trunk or have a direct connection to its anatomical structures. For example, the position of the pelvis, for example during flexion or extension of the hip joint (Figure 2), continues to affect the lordosis in the lumbar spine.[102] Also, the fascial extensions of the gluteus maximus have a connection to the deep thoracolumbar fascia.[112]

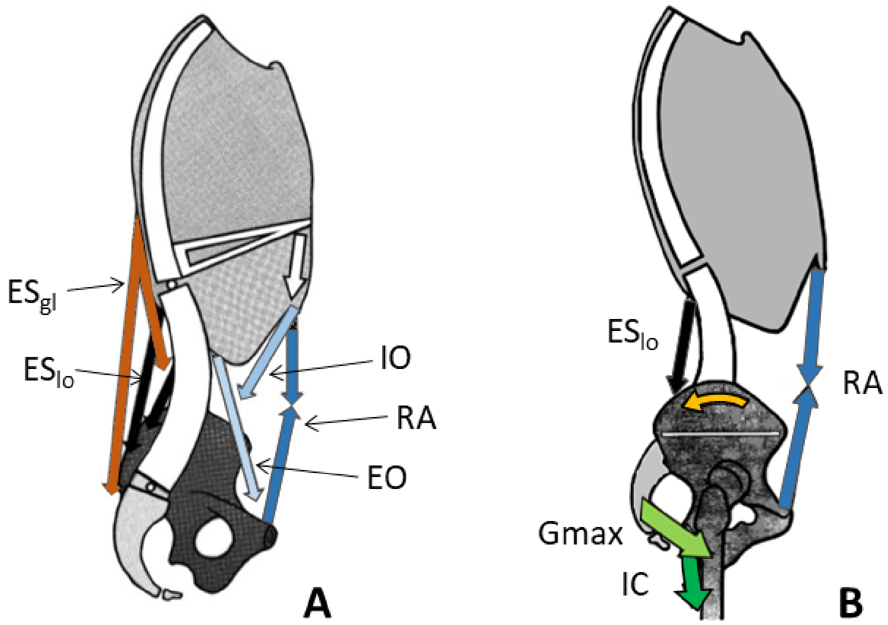

Figure 2: Schematic illustration and model of the muscles involved in the spine movement and stabilization of the trunk displayed in the drawing modified from Bergmark et al.[15] and Kapandji.[61]

A: The global system is formed by muscles not directly attached to the spine, but able to transfer load from the pelvis to the thoracic cage (ES_{gl} (brown), IO, RA, EO (blue arrows). **A/B:** Local erector spinae muscles (ES_{lo}; black) is directly attached to the lumbar spine and forms and stabilizes the lordosis. **B:** Gluteus maximus and hamstrings (light and dark green) act as synergists to the abdominals represented by RA and can also reduce the lumbar lordosis. The yellow arrow represents the corresponding pelvic alignment. ES_{lo} works antagonistic to this movement, aiming to stabilize the lumbar lordosis.

Abbreviations: ES_{gl}, global erector spinae muscles; ES_{lo}, local erector spinae muscles; IO, internal oblique; RA, rectus abdominis; EO, external oblique; G_{max}, gluteus maximus; IC, ischiocrurales/hamstrings.

Core stability and trunk strength

Muscular strength can be considered as a key to athletic performance in many disciplines, as a direct relation from force to performance is provided.[104] Comparing core muscle function to the way limb muscles work one can observe mechanical parallels. When it comes to securing joints and limiting joint movement, the muscles around a joint activate in a so-called co-contraction. A co-contraction can stabilize the joints of the extremities as well as the trunk, including the spine. The core muscles often co-contract to stiffen the trunk, whereby all muscles act as synergists.[72] Whether the body chooses limb or trunk co-contraction in response to instability appears to vary with age. During balance tasks older adults tend towards higher co-activation in the ankle joint while younger adults show this more pronounced in trunk muscles.[41] The term core-stability reflects this coordination of the activation of different muscles of the trunk. The primary task of the trunk muscles is preventing the spine from tilting or buckling.[102] In this context, the spine is often referred to as an inverted pendulum.[56] Therefore, with regard to the performance of the trunk muscles, parts of the literature focuses more on core stability rather than trunk muscle strength as the subject of investigation.[9; 33; 78; 109] For everyday stress such as walking and standing, the obvious approach is to keep the spine vertically in a balanced and stable as well as energy-efficient position. This function is a prerequisite for almost all motor tasks. However, when the trunk is exposed to high or long-lasting loads such as jumps, sprints, lifting weights or long-distance running, additional abilities concerning strength are required. Besides questions related the issue of stability, the question of different functions of trunk muscle strength might raise additional issues, such as, for example, whether maximal strength or endurance is more crucial while jumping. For the function of the spinal column, however, stability and strength are inseparably linked. Strength training will affect stability, as will stability training improve strength performance, both in orthopedic therapy and in sport.

It is assumed that the spinal column would be unstable without active muscles since, in an in vitro scenario, the osteoband-like lumbar spine deforms under a pressure load of merely 90 N.[36] Panjabi[89] describes the prerequisites for spine stability by illustrating the coordinated influence of three subsystems which coat the skeleton. The first is the passive subsystem in which the support and the direction of movement are determined by the structure of the vertebral bodies and the passive structures such as intervertebral discs, ligaments and capsules. Experimental studies and clinical findings verify that mechanical deformation can lead to a larger "neutral zone" and joint instability while inflammatory mediators also have to be taken into account.[79] The second active subsystem consists of all muscles and tendons that surround the spine and can absorb forces acting on the spine.[89] The peripheral and central nervous systems form the third, neuronal subsystem. The neuronal system collects information about the position and pressure of the spine using mechanoreceptors while recording tensile and compressive conditions in the joints and muscles.[59] Signals from the first two subsystems are processed on spinal and cortical levels[105] and from there the active subsystem is controlled to ensure the necessary stability in the trunk.[89; 110]

McGill[78] notes that there is no single muscle that stands out as the most relevant stabilizer of the spine. The most important muscle is determined by the task to be solved and therefore varies from one motion to another. Nevertheless, all muscles of the trunk work together continuously to ensure balance and sufficient stability in all degrees of freedom. McGill[78] stresses the importance of muscle endurance (not strength) and "healthy" motor patterns to ensure stability. He formulates unsolved questions, in particular in respect to “(1) understanding the role of various components of the anatomy to stability—and the ideal ways to enhance their contribution; (2) understanding what magnitudes of muscle activation are required to achieve sufficient stability” (p. 358).[78] However, Wirth et al.[116] critizise that the literature on core stability training tends to focus solely on muscular activation. The authors noted that the majority of the investigations focus on central nervous processes whereas morphological adaptations of the structures involved are not sufficiently addressed. The efficiency of exercises typically applied and their applicability to athletes are also rated as being insufficient.[116] While the stability approach mostly emphasizes motor patterns and muscle activation[78; 110], Wirth et al.[116] suggest that more attention should be given to muscular strength abilities. The authors point to out the necessity to investigate muscle quality and the associated strength abilities more closely, especially in the field of sports. Indeed, this aspect has rather been neglected as the majority of previous studies mainly focused on trunk strength endurance ability[78] or followed the core stability approach.[93] On the other hand, there is no fundamental difference between the strength ability and the stability approach as both refer to the same subsystems and structures. Both approaches have not yet provided a clear solution for assessing or eliminating trunk strength deficits. Thus, at least the consideration of further inquiries and approaches is a reasonable assumption.

Trunk strength assessment

To quantify trunk strength or core stability, a great variety of assessments have been described. Waldhelm et al.[114] have enumerated no less than 35 different tests which could be applied to measure core stability. However, it remains unclear which test or exercise exactly can best estimate trunk strength best. Depending on the underlying assumptions and scientific approaches either strength- or endurance-related measures of core performance have been used in previous studies.[48; 74] The following subsections list generally accepted and applied trunk performance assessments together with their respective methodological strengths and weaknesses. The purpose of the measured trunk strength should thus become more apparent. The results of different modes of trunk strength assessments are often used to calculate strength ratios between the opposing directions of spine movement. In the end strength outcomes or ratios are often related to physical performance[85; 88] or, eventually, the occurrence of pain.[46]

Maximal isometric trunk strength testing

For isometric trunk measurement either a mobile[38] or stationary force gauge is used.[40] Isometric trunk force measurements can be carried out in all degrees of freedom of the spinal movement (flexion, extension, rotation, lateral flexion) in a sitting and standing position.[65] With isometric contraction muscle tension increases without muscle shortening. The magnitude of the change in muscle tension can be measured using different methods. In biomechanics measuring sensors with strain gauges or piezoelectric sensors are the most frequently utilized devices. When loads are changing, there is a change in voltage which can be recorded with the appropriate measuring device. The measured force values are usually displayed as a force curve and can be evaluated with regard to the maximal force production as well as the rate of force development over a defined time period. The sampling frequency of the assessment tool plays a decisive role in the evaluation of the obtained data. Careful attention also needs to be given to anatomical differences between subjects, e.g., body weight or upper body length.[16] Therefore, relative values, such as strength relative to body weight, needs to be reported in most instances. Strengths of isometric testing are lower coordinative requirements as is the ability to adjust any desired joint position angle. A weakness can be seen in the potentially high loads on the passive structures in unfavorable angle positions. Finally, an assessment of the different forces playing out during dynamic movements remain impossible.

Isokinetic trunk strength testing

Isokinetic strength testing requires expensive devices which are usually situated in a laboratory. Theoretically, isokinetic trunk strength assessment can also be performed in all movement directions of the spine. However, some devices are limited to the degrees of freedom (Figure 3). In addition, the position and the fixation of the participants can differ between devices complicating the comparison of results difficult.[58; 70] Isokinetic (iso = equal; kinesis = movement) strength measurements are performed with a specified fixed speed of movement and are possible during concentric or eccentric contractions. The selected speed of movement depends on the research question to be answered. Slower velocities (up to 60°/s) result in higher torques and show fewer measurement artifacts at the turning points, while higher velocities are better suited for the investigation of strength endurance capacities.[81] The measured values are usually displayed as force or torque curves. They can be evaluated in terms of peak torque, defined as the highest point of the curve over time, work per repetition, torque over time,[40] and torque at specific angle positions.

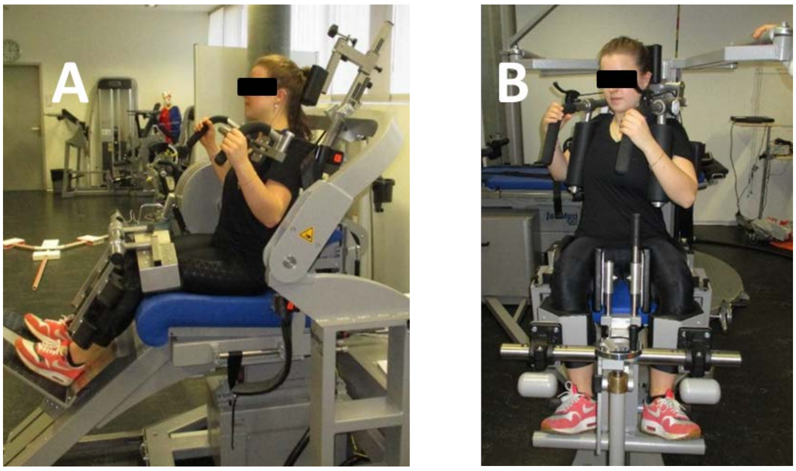

Figure 3: (A) Assessment of trunk strength flexion and extension on an isokinetic device (IsoMed 2000). (B) Assessment of trunk strength in horizontal plane with adapter for trunk rotation. The athlete is tightly fixed at thighs and upper body to keep evasive movements to a minimum.

Beimborn et al.[14] present an overview of norm values and ratios between trunk movements like extension and flexion as well as rotation and lateral flexion for women and men. The authors describe a large variability which they primarily attribute to methodological differences (e.g., regarding movement speed and position) and the parameters obtained (peak torque or work). For example, peak torque extension/flexion ratio has been reported to range between 1.0 and 2.0, with approximately 1.3 being the most frequently reported ratio. Thus, in most cases, trunk extensors are expected to be 30% stronger than the flexors.[14] For rotation and lateral flexion, most researchers found a side-to-side ratio of about 1.0.[37; 103]

The isokinetic devices are usually very expensive, which limits their use. Additionally, the positioning of the subjects is given and rigid. Therefore, strength cannot always be tested at the desired joint angle as applied in functional movements. Natural movements are typically not performed in an open kinetic system. Some authors, however, refer to isokinetic strength assessment as the “gold standard” for measuring the strength of trunk muscles, as this assessment method can be standardized very well.

Trunk strength endurance

The most commonly used method for assessing the capacity of the trunk muscles probably is testing trunk strength endurance. The measurement of trunk strength endurance illustrates a person's ability to maintain a defined posture or to perform a defined movement for as long as possible with or without external load. Defined positions have to be maintained either until the position has to be given up or for a defined duration during in which the number of repetitions is counted. The resulting score should allow an assessment of the performance of the trunk muscles involved. Strength endurance can also be assessed with isokinetic devices in which the amount of force loss is recorded during a specified number of repetitions.[8] Many tests have their origins in the treatment and therapy of back problems. Some of them have entered the field of sports. Due to their easy implementation, they have found wide application. They often require only a few additional devices and are not bound to a specific location. In the following some of the most common tests are presented in detail.

Biering-Sørensen test

In 1984 Biering-Sørensen[16] designed an isometric endurance test of the back muscles which henceforth has become referred to as the "Biering-Sørensen test" or "Sørensen test". Ever since its inception different variations have been created with different names attributed to them, with "extensor endurance test"[77; 96; 101] or "dorsal trunk muscle chain test"[24] being the most frequently used. The test is usually performed in a prone lying position on a bench with hips extended, legs strapped to the bench and the upper body held unsupported horizontally from the upper border of the iliac crest, the arms folded over the chest. The time until which a participant can no longer control his posture and reaches his limit of tolerance by showing signs of fatigue is measured. The test was originally limited to 240 seconds.[16] As a variation, the test is also conducted with bent hips[42] (i.e. for seniors) or with additional dynamic upper body movement between two defined points.[108] As shown in Figure 4, with the help of a scaled stand with two height-adjustable bars, a standardized movement space is given between level and 30° flexion. In the most current variation, the bars must be touched alternately in a given rhythm and the time spent until the abortion of the test is measured.

Figure 4: Biering-Sørensen test, dynamic variant, touching alternately the upper and lower bar (picture) in a given pace during a testing procedure.

Prone plank test[24]

In the prone plank test only the forearms and feet serve as support while the upper body and legs do not touch the floor. Participants are usually instructed to “form a straight line” from the toes to the shoulders/head. This test aims to hold the straight (elevated) position for as long as possible. The test is over when the subject is unable to hold the back straight and when the hip is lowered. The score is the total time completed. Advantages of the test are the minimal (or non-existent) costs. In addition, the test can be conducted statically or dynamically by lifting the legs alternately at a given pace. However, the exact determination of the point at which whether a failure occurs, and if it occurs at all, remains a subjective assessment without the necessary equipment at hand. As shown in Figure 5, evasive movements can be made obvious to standardize the measurement. By restricting the movement of the upper body (wall in front of the head) the movement of the shoulders in relation to the elbows can be prevented and the position of the sacrum can be traced by a horizontal bar.

Figure 5: Prone plank test with alternating leg lifting and inclinometer for sacrum position control.

Side plank[24] or side bridge[77]

The side bridge test is performed while lying on the side with the legs stretched out (Figure 6). The feet are either placed on top of each other[24] or with the upper leg in front of the lower leg.[77] The subjects are instructed to lift their hips off the mat and to keep the entire body in a straight position. The participants are supported at their forefoot and at their elbow, with the latter being placed perpendicularly under the shoulder joint. In the static mode the time to fatigue is defined as the duration in which the participant manages to hold the hip off the ground.[77] In the dynamic mode the participant is asked to move the hip up and down according to a defined pace set by a metronome, touching the floor on the bottom and a bar at the top with the trochanter major. The test result represents the time until the movement between the bottom or top point can no longer be maintained.[24]

Figure 6: Side plank test, touching the upper bar during a dynamic test procedure.

Flexor endurance test[77]

The trunk flexor test is a testing procedure used to assess the endurance capacity during an isometric contraction of trunk and hip flexors. Participants are asked to sit on a bench, with the back supported by a backrest with an inclination angle of 60° (Figure 7). For the measurements the backrest is pushed back 10cm and participants are asked to hold the position for as long as possible without touching the backrest. Following the setting of the previous tests the time to fatigue is measured. The test ends when the upper body falls below the 60° line. Similar dynamic tests are the repetitive sit-up or repetitive arch-up test (not shown).[3]

Figure 7: One of "the Big 3"[72] to test trunk muscle performance: Flexor endurance test at 60° without backrest.

McGill[72] designates three exercises as "the Big 3" (Biering-Sørensen test; side bridge test; trunk flexor test). These three exercises are considered to provide a meaningful description of trunk muscle performance. In an early work from Alaranta et al.[3], these tests have been established as standard testing procedures in a variety of sports disciplines for both men and women and have been used repeatedly thereafter. A variety of other tests are also associated with trunk strength or stability. Tests like the leg lowering test and trunk raising test are not mentioned yet but are also used as scalable function tests. Many tests have proven to be highly reliable.[76; 108; 114] Normative endurance times were collected and relative ratios for clinicians were proposed.[77] However, it has also become obvious that measured parameters can change with the composition of the study population and should therefore be considered with caution.

Trunk strength and sports performance

As described above the assessment of muscle strength can be carried out in many ways. In sports, for instance, it is commonly applied that the assessment of the isolated forces is provided in open kinetic chain, i.e. during knee extensor exercises by an isokinetic device. Similarly, the performance of the entire leg extensor chain can be tested by free weight squats in order to assess the one-repetition maximum (1RM). The latter type of measurement is often performed because of the high correlation between sport specific tests and performance, i.e. free weight squats and 10 m sprint performance.[71; 116] In contrast, the isolated force measurement at single joints is more standardized even though the relationship between strength and performance in the open system remains unclear.[86] As mentioned previously there are many different ways to assess trunk strength. Given that there are many degrees of freedom in the individual movement this does not seem to come as a surprise. And there are many functional options of including the upper, lower, or both limbs in the movements assessed. The wish of athletic trainers is to understand the magnitude of the relationship between trunk muscle strength and athletic performance.

In a recent meta-analysis Prieske et al.[90] examined a potential relationship between trunk muscle strength and athletic performance in trained individuals. The included studies measured trunk muscle strength with different methods, including, for example, isometric maximum strength, strength endurance, or leg lowering test. The authors stress the large variability of trunk muscle strength tests applied in the analyzed studies. Interestingly, trunk muscle endurance assessed by the prone plank test was the most common assessment method.[90] In the studies included in their analysis athletic performance was tested, measuring maximum power output of the limbs, sprint performance, maximum ball velocity, change-of-direction sprints, and balance performance. The authors only found small correlations between trunk muscle strength and athletic performance and conclude that trunk muscle strength is only of minor importance for athletic performance. They also maintain that an improvement in trunk muscle strength provides little additional benefit for athletic performance.[90] Similarly, Barbado et al.[8] examined the relationship between trunk strength and performance in 25 male judokas on an international and national level and only found low correlations between trunk strength and performance. Trunk strength performance was tested with a strength endurance assessment on an isokinetic device (concentric/concentric at 120°/s, 15 repetitions). The performance tests included sudden perturbation loadings on the trunk and measurements of sitting trunk balance. The authors conclude that higher level judokas showed a better endurance of trunk extensors and performance in anterior trunk loading than lower level athletes. The higher back extensor force capability of high-level judokas is obvious and plausible, as they are more often exposed to also higher forces (due to stronger opponents) than athletes who only fight on a national level. Testing the maximum strength of the trunk extension rather than strength endurance might have been more appropriate to demonstrate the presumed differences in strength and performance between competitive levels.

It seems obvious that a strength endurance test cannot provide sufficient information about the athletic performance in a maximum strength test.[27] An explanation for the omission of maximum trunk strength testing could be based on the observation that maximal measures of trunk strength are considered to be potentially dangerous for trunk muscles, depending on the physical status in respect to strength, mobility and movement control.[72] In sum, previous studies demonstrated only a marginal correlation between results of trunk strength assessments and athletic performance. As pointed out above these findings do not reflect to the expectations of trainers and therapists.

Trunk Muscle Activity

Based on the current literature, a direct measure of trunk stability is not available.[62] Thus, most studies focused on muscle activation profiles,[13; 67; 80] assuming that in vivo assessments of trunk muscle activity allow to conclude on the effectiveness of neuro-muscular control. Surface electromyography enables us to display activation profiles as well as the analysis of muscle recruitment strategies.[49] Many authors have shown that the activity of the deeper abdominal and back muscles can be reliably derived from surface electromyography (EMG).[35; 54; 75] However, both the points of attachment and the possible contamination in the EMG signal by neighboring or layered muscles must be taken into account.[21; 52; 57] In addition the normalization to maximum isometric contractions[28] and the filtering of heartbeat[30] are methodological issues which need to be taken into account.

There is broad consensus among authors in the field that a higher activation of trunk muscles accompanies increasing demands on spine stability.[5; 62; 111] This is confirmed by studies which show that more complex, functional movements, e.g. increasing load with free weights or unstable surfaces,[4; 34] can result in a higher activation of the trunk muscles. Especially the back squat to parallel (thighs at horizontal) at a load of more than 50% of 1RM is described as an effective method for trunk muscle activation and, thus, potentially for trunk muscle training.[34] Most studies which seek to determine trunk muscle activation in strength exercises or which investigate the relationship between trunk muscle activation and the occurrence of back problems are cross-sectional studies. However, one of the few intervention studies evaluating trunk muscle activation after a four-week trunk strengthening program reported no altered muscle activation during a two-hour standing load.[84]

Surface EMG can also be used for the evaluation of fatigue-related changes in muscle recruitment. It is commonly accepted that fatigue during a sustained isometric contraction not only results in changes in EMG amplitudes but also in an altered frequency band.[39] For example, a sustained sub-maximal contraction results in a linearly increased amplitude of the EMG to which a decreasing firing rate and increasing force twitches contribute.[39]

The use of EMG, therefore, allows for conclusions about different aspects of neuromuscular performance, namely the degree of activation (compared to a maximum contraction), fatigue-related changes with respect to EMG amplitudes, EMG frequency bands, and the exact definition of the onset of activation.

Prevention and Rehabilitation

The trunk is often regarded as the central stabilizer of everyday activities but also of sports movements. Therefore, core strengthening exercises are an integral part of injury prevention programmes[17; 20; 95] and for treating back problems.[2; 73] Some evidence shows that better trunk strength can lead to reduced back pain,[10; 55] and decreases the risk of injuries of the lower extremity[115; 117] and of overload-induced injuries.[45]

Early studies already established a correlation between reduced muscular endurance of the lower back muscles with increased back pain.[76; 87] For instance, as early as in 1958[46] Flint investigated if an intervention targeting the trunk muscles affects back pain. He concluded that "symptomatic relief was obvious, as muscle hyperthrophy and performance increased"(p. 160). Based on these early studies the recommendation of physical exercise for the prevention and/or rehabilitation of back pain now is widely accepted.[100] However, there is insufficient evidence in favor of one particular type of training defined at a specific frequency or intensity.[29] A satisfactory assessment of the efficacy of these exercises still is missing.[6; 13; 31]

Back problems in athletes are a common problem[106] – despite their frequent physical exercise. The mechanism responsible for back problems might differ from athletes to inactive persons. As mentioned above, physical inactivity or long periods of sitting might trigger back pain to a variety of different persons. In contrast, physical inactivity cannot elicit back pain in frequently active athletes. In fact, the occurrence of back problems is higher in sports with additional loads or high accelerations and/or decelerations.[7; 106] In addition, a higher incidence of complaints can be found during the preparation and competition phases compared to the active recovery phases.[7] Based on these observations, there is an ongoing debate whether athletes are not sufficiently prepared for the loads that have to be tolerated during the intense training and competition phases.[18; 47] To the author's knowledge, no study with athletes could demonstrate, yet, that higher trunk muscle strength is associated with less back pain.[94] This may be due to the fact that, in addition to strength, mobility, and coordination, the structures involved like tendons, insertions, discs, and ligaments contribute to the outcome of pain. From a functional perspective, the adjoining musculature, such as hip extensors and flexors, also need to be taken into account as they have an indirect effect on the trunk and the spine.

Core strength training also is viewed as a useful means for the prevention of lower limb injuries.[2; 17; 83; 115] However, given the range of quite different variables which define the setting of the tests it seems difficult to assess whether trunk strength training was the sole cause of an observed effect. It has to be noticed that (I) although trunk strength exercises are part of nearly all evidence-based prevention programs, they are only one part of a multimodal approach, including additional leg strength, plyometric and balance exercises. (II) It is difficult to train the trunk musculature in an isolated manner without activating the hip musculature, as it exerts a great influence on the stability of the leg alignments. (III) The majority of the studies are conducted in recreational sports where additional training can produce considerable effects. Therefore, the decline in injury rates seems to confirm the effectiveness of the intervention programs listed above as solid, but the precise contribution of increased core stability to the outcomes remains an open question.

Relevance and aims

A logical response to the high strength requirements in sports seems to be the strengthening of muscles, particularly those of the trunk as discussed here. The trunk muscles are trained to protect the body against overloads and injuries, but also to improve performance in many sports.

Evidently, our knowledge as to how, and to what degree muscular performance and activation of trunk muscles as well as strengthening exercises of this part of the body contribute to a desired effect remains rather inconclusive. With patients with lower back problems there are indications that a higher strength endurance capacity of the back muscles alleviates the problem.[46] It has also been shown, particularly with women, that the majority of trunk strength programs have a positive influence and produce a lower frequency of lower limb injuries.[17; 66] However, there is still no conclusive explanation for these results.[93] However, the findings supporting the hypothesis that trunk strength has a positive effect on performance in sport also remain to be very inconsistent and inconclusive.[44; 64; 72; 85; 88]

The presented thesis therefore aims:

- to examine the magnitudes of muscle activity in different exercises (study°1,°4)
- to understand how high the contribution of the trunk system is (study°1,°3,°4)
- to analyze and differentiate the measurement of different abilities of trunk strength (study°1)
- to evaluate the reliability of trunk strength testing (study°2)
- to evaluate a new approach estimating the impact of trunk strength capacity on sports performance outcomes (study°3)

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Outline

This cumulative thesis comprises four publications dealing with three closely related research questions: (I) To what extent is the strength of the trunk musculature interrelated with sports performance, (II) how can strength of the trunk musculature best be measured, and (III) how does trunk muscle strength contribute to exercises? The manuscript in *Publication 1* provides a comparison between laboratory and field tests. *Publication 2* evaluates a laboratory method regarding its reliability, while *Publication 3* focuses on the interrelation between trunk strength and athletic performance. In *Publication 4,* the activity of trunk muscles during squat exercises is presented.

Publication 1 describes how and why trunk strength tests in the laboratory and in the field do not necessarily measure the same construct. When assessing trunk strength, aspects of local endurance capacity, peak forces and neuromuscular requirements should be taken into account. Even though the reported values are always referred to as strength values, the used measurement methods are not comparable. This is relevant as an important question in the design of studies is what tests should be chosen in order to answer the research question. The aim of this study was therefore to compare performance and muscle activation during a global trunk endurance test applicable to field conditions regarding its transferability to a maximum isometric force test in the laboratory. The applicability and relevance of the two tests are described. The difference between the two tests is presented and discussed, accompanied by EMG measurements of the trunk muscles.

Publication 2 addresses the reliability of isometric testing procedures for trunk strength assessment. In this study, torque was measured on four different days with different trunk movements such as flexion, extension and rotation in both directions. The movements were performed at speeds of 60°/s, 150°/s and in isometric mode. Intraclass correlation (ICC) and coefficient of variance (CoV) were calculated and presented as reliability index together with minimal detectable changes.

Publication 3 addresses the influence of trunk or leg strength on athletic performance. Thereby, our methodological approach was based on separately fatiguing leg and trunk muscles and analyzing the changes in selected performance outcomes. Sprint, change-in-direction and balance ability are important prerequisites for many athletes to perform at highest levels. We hypothesized that fatigue-induced impairment of trunk or leg muscle decreases performance output, but to a different extent depending on the observed outcome. Before and after a 20-minute fatigue-inducing exercise protocol, sprint time, time in an agility test and balance tasks as well as trunk and leg strength were measured. The results of these tests provided us with the opportunity to compare the influence of the different muscle groups on athletic performance. This allows for drawing a conclusion on the relevance of the strength of the trunk muscles in athletic performance.

Publication 4 evaluates the activity of trunk musculature while performing different types of squats. Loaded back squat, front squat and overhead squat were performed conventionally and with reduced base of support by standing on the forefoot. During the squatting movement, muscle activity of the abdominal and back muscles were recorded by EMG as well as the center-of-pressure path way was assessed using force plates. Motion capture analysis enabled to examine for examining the kinematics of the squat movements and to calculate the lumbar lordosis angle. Differences in the squat types regarding muscle activity, CoP and lordosis angle are described and discussed.

Publication 1

Muscle activation and performance during trunk strength testing in high-level female and male football players

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Publication 2

Absolute and relative reliability of isokinetic and isometric trunk strength testing using the IsoMed-2000 dynamometer

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Publication 3

Acute leg and trunk muscle fatigue differentially affect strength, sprint, agility, and balance in young adults

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Publication 4

Trunk muscle activity during different types of squat exercises in normal and forefoot standing conditions

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Abstract

STUDY DESIGN: Cross-sectional study.

BACKGROUND: Squat exercises are regularly used in athletic and rehabilitation settings to strengthen leg muscles, but little is known about trunk muscle requirements during such exercises.

OBJECTIVES: To evaluate leg and trunk muscle activity when performing three squat types: back (BS), front (FS), and overhead squats (OS) techniques from a stable and unstable position base of support.

METHODS: Twelve healthy adults (N = 6 women, age: 29.4 (SD 9.0) y, height: 168.5 (6.0) cm, body mass: 64.0 (7.1) kg and N = 6 men, age: 28.8 (8.0) y, height: 178.3 (3.1) cm, body mass: 76.2 (6.6) kg) randomly performed FS, BS, and OS with a barbell (women 12.5 kg / men 20 kg). Surface electromyography from external (EO) and internal (IO) oblique, rectus abdominis (RA) and erector spinae (ES) were recorded and normalized to a maximal voluntary isometric contraction (MVIC). 3-D motion of the lumbar spine was measured using a motion capture system along with the center of pressure path length (CoP) from a force plate. All data were evaluated for the lowering, turning, and raising phases.

RESULTS: Highest percent of MVIC muscle activity occurred in EO and ES. The unstable condition (reduced base of support) did not change overall trunk muscle activities (.05<Hedges’ g<.29) while the type of squat did (BS<FS<OS). IO and RA muscle activity were similarly low in all conditions (2.1-10.2% of MVIC). The unstable condition revealed a longer CoP path length (.45<g<1.3). Greater spinal curvature occurred during the FS and OS (.61<g<.78).

CONCLUSIONS: Squat exercises engage both dorsal and ventral trunk muscles. Increasing the difficulty of the squat through front or overhead loading, or by performing them on an unstable surface increases their level of their activity, which has implications for training and rehabilitation.

KEY WORDS: strength, EMG, core, balance, resistance training, rehabilitation

LEVEL OF EVIDENCE: Therapy, level 2c

INTRODUCTION

The squat is an integral part of strength training for athletes[1,26], for general fitness[1,4] as well as for rehabilitation.[10,27] To improve or maintain individual performance levels, the squat can be performed various ways, with the three most common being the back squat (BS), front squat (FS), and overhead squat (OS). The muscle groups primarily targeted for the squat are the knee and hip-extensors and calf muscles, as these provide significant power for propulsion and stability of the pelvis during walking, running and jumping, as well as during many sports activities where rapid accelerations and deceleration, as well as changes of direction, are required.[17,31]

Squat exercises are performed either without, but more often with, additional load to increase strength and optimize training outcomes. Loaded squat exercises require additional stabilization of the trunk and spine, presumably through activation of the trunk muscles.[18] The concept of trunk stabilization assumes that back muscles (erector spinae) help to maintain the thoracic spine as a stable segment[19,33] while the abdominals play a role in controlling the lumbar vertebrae to prevent excessive curvature (hyperlordosis).[13,22] For that reason, most studies investigate rectus abdominis, internal and external oblique and erector spinae muscles[14,28,38] concerning stabilization of the trunk, as pelvic muscles and deep abdominals, as well as the involved diaphragm, are challenging to measure objectively.[20,36] It has been observed that during the lifting of (heavy) loads, surface electromyography data shows[37] that both ventral and dorsal trunk muscles are often activated in a particular order to stabilize and protect the spine against unsafe loading and potentially prevent injury.[3,30]

As such, the contribution of trunk muscles should also be considered when performing a squat, as they may be a critical factor in stabilizing the trunk to safely support the required additional load. Insufficient stabilization of the trunk may be a limiting factor in terms of controlling the load, but more importantly, may be a potential risk factor for injuring the spine and its surrounding structures.

Squat exercises may be a suitable way to train the trunk musculature to control the torso, as loading can be progressively added during training. In recent years, unstable strength training and squatting have become an increasingly popular training method used to induce specific metabolic and neuromuscular adaptations.[2,5,9,18] Intuitively, unstable resistance training methods are appropriate as many daily and sports related movements are performed in a changing environment where balance is crucial.[11,27] There are studies that have compared the effect of strength training exercises performed on stable and unstable surface, but the benefits of training on an unstable surface are currently equivocal.[12,28] Training exercises, such as a squat, performed on an unstable surface[24] should theoretically result in an increase in the activation of the abdominal and back muscles to control the motion of the trunk and supported load, as the ability to produce corrective torques about the ankle can be limited when standing on an unstable surface, or standing on a reduced base of support.[18]

A literature search reveled that there are studies that have investigated activity of the leg muscles during different squat techniques (i.e., BS, FS) and on different surfaces.[28,30,32,34] However, data concerning the activity of the abdominal and back muscles during different types of squats is not as extensive.[28]

As mentioned earlier, it is currently unknown to what extent different types of squatting exercises, performed on an unstable surface, or reduced base of support, might have an affect on trunk muscle activity, as well as spinal curvature which is largely controlled through trunk muscle activation. Therefore, this study aimed to compare abdominal and back muscle activity in healthy adults while performing a variety of loaded squatting exercises on a stable surface and on a surface with a reduced base of support which is known to challenge balance. We hypothesized that a performing a squat while on the balls of the feet only, would increase the activity of the trunk muscles due to an increased demand to stabilize the trunk and load. A secondary hypothesis was that performing a squat with the external load moved to the front of the torso, or to an overhead position, would result in a redistribution and change in magnitude of trunk muscle activity[28], as well as influence spinal curvature. An expected outcome of the study is an improved knowledge of how squat exercises can be used as an appropriate training protocol for both leg and trunk muscles in novices and rehabilitative training.

METHODS

Participants

Twelve healthy adults (N = 6 women, age: 29.4 (SD 9.0) y, height: 168.5 (6.0) cm, body mass: 64.0 (7.1) kg and N = 6 men, age: 28.8 (8.0) y, height: 178.3 (3.1) cm, body mass: 76.2 (6.6) kg) participated in the study. All were physically active individuals with no known injury or condition that would affect their ability to perform the required exercises. To focus on a set of inexperienced athletes in rehabilitation, we aimed at measuring persons with low experience in weight lifting. All subjects read and signed a consent form before measurements and the protocol was approved by the local university ethics committee and conducted according to the Declaration of Helsinki.

Three different squatting exercises were performed in a randomized order: i) back squat (BS), ii) front squat (FS) and iii) overhead squat (OS). On the same day, before testing, participants were familiarized with how to perform each type of squat. Testing consisted of each participant completing four repetitions of each type of squat while standing barefoot on a split force plate (AMTI, Watertown, USA) which collected the path length of the center of pressure (CoP) derived from the ground reaction forces and moments. Initial trials were performed from a normal standing position while subsequent trials were performed with a reduced base of support by standing barefoot on the balls of their feet on a 1.6 cm high wooden that prevented their heels from contacting the ground. The forefoot condition was introduced to increase postural instability during the squat, which supposedly increases the recruitment of trunk muscles to control the torso. Independent of squat type or standing condition, participants were loaded with a barbell of fixed mass (12.5 kg for females, which was 22 ± 4% of their mean body mass and 20 kg for males, which was 26 ± 2% of their body mass). The beginning and end of each squat was defined when the knees were fully extended, and their trunk stationary (Figure 1). The bottom turning point was set to correspond to an internal knee flexion angle of 100°, which corresponded to when the subject felt contact with their buttocks to a fixed bar positioned behind them at the required height. These specific points were defined as “start”, “turning point”, and “end” of the squat. The required timing to complete each squat was 2-s down and 2-s up, which was set by an acoustic signal. A 4-s period, standing in an upright position, was used to separate each repetition. Foot width and angle was self-selected by each participant and documented. Participants were required to stand in the same position for all trials and focus on a point 4 m in front of them, at head height, during the squat.

Measurements and instrumentation

Surface electromyography (EMG) was used to quantify muscle activity during the different phases of the squat. EMG signals were measured from four muscles on the right side of the trunk:[7] external oblique (EO), internal oblique (IO), rectus abdominis (RA), and erector spinae (ES). Bipolar electrode configurations were used (2-3 cm electrode separation) and placed over each muscle, according to the SENIAM guidelines, and parallel to the expected fiber orientation.[7] Prior to electrode placement the skin was prepared by shaving and abrading the skin with an abrasive gel (Nuprep, Weaver and Company, USA) to keep the electrode resistance below 5 kΩ.

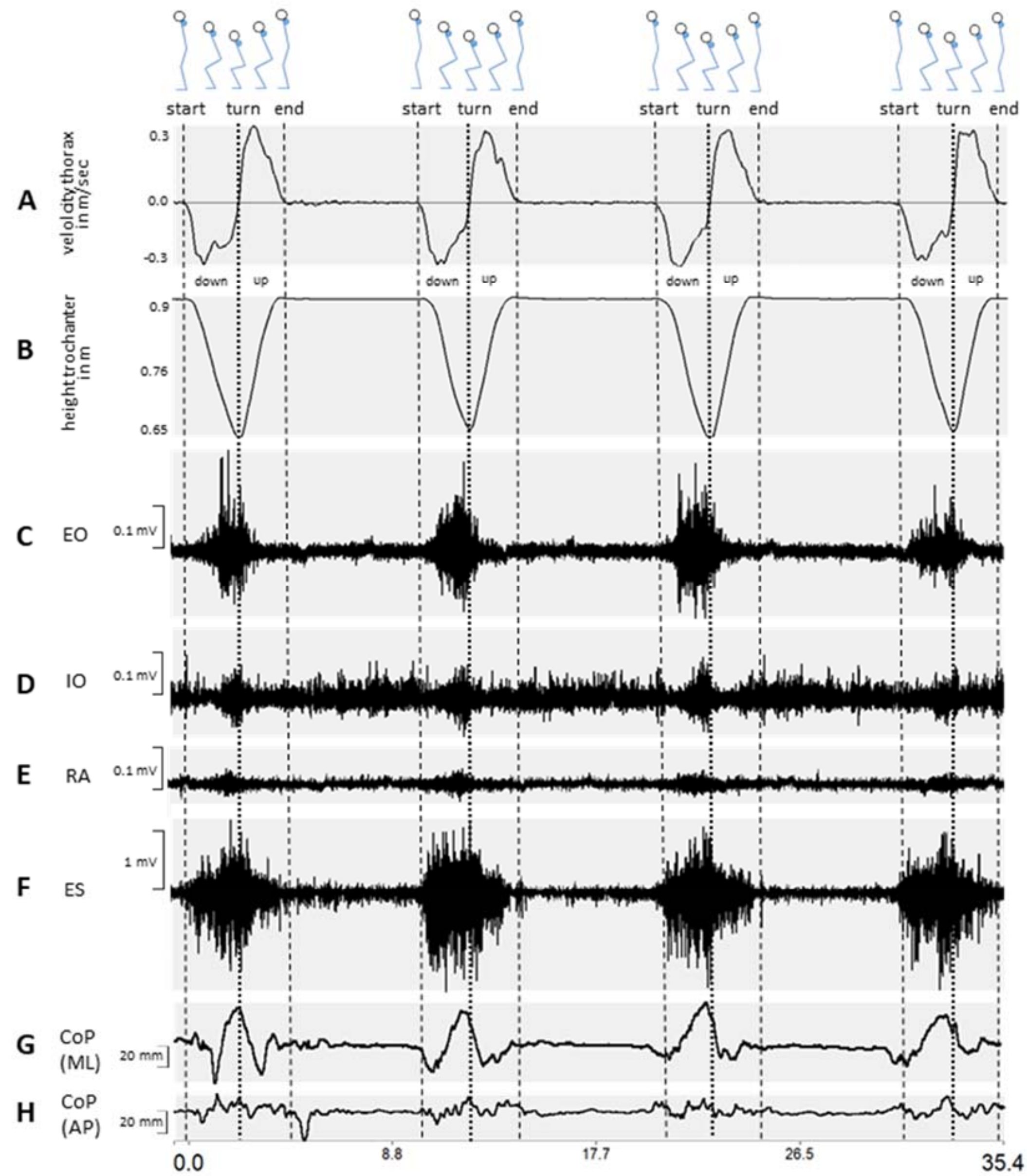
EMG signals were amplified 100 times (model NL 844 preamplifier, Digitimer), band-pass filtered between 10 and 1000 Hz (model NL 900L, Digitimer) prior to analog-to-digital conversion at 2 kHz using a16-bit using a Micro 1401 mk-II (Cambridge Electronic Design, UK) and commercially available software (Spike2, Cambridge Electronic Design, UK). Three time-intervals were analyzed concerning the three phases of the squat: lowering, turning point (1 second) and raising. EMG data was normalized against an attempted maximal voluntary isometric contraction (MVIC). For trunk flexion, participants performed a crunch in a supine position, while trunk extension was measured by extending the back while the trunk and the legs were fixed with a belt in a prone position. MVIC activity was determined from a stable period (3-5 s) of maximal activity during the task.

Movement of the thorax, a virtual point between the sternum and C7, was used to describe the squat positions and was determined using an eight-camera, opto-electronic motion capture system (Qualysis AB, Gothenburg, Sweden). 3D position and motion of each participants' torso and lower limbs was captured using 56 single reflective spherical markers (diameter = 19 mm) placed on the feet, medial and lateral femoral epicondyles, posterior and anterior superior iliac spine, spinous process TH12 to L4, Thorax, and middle of the third metacarpal bone. Marker clusters (groups of 4 markers mounted on a rigid plate) were attached to the lateral side of the thigh and shank. The position of the markers was sampled at 200 Hz using computer software (Qualysis Track Manager, Qualysis AB, Gothenburg, Sweden) and analyzed offline (Visual 3D, C-Motion Inc., Germantown, U.S.A.). Before the beginning of each assessment, the motion capture system and force plates were calibrated, and subsequently, a static standing trial was captured. The knee, as well as hip angle and the angle between the TH12 – L2 – L4, were calculated. The latter can be used as a measure of the lumbar spine angle.[40] Path length of the center of pressure (CoP) for the entire squat (start to end) was calculated from the two force plates according to the equation of Winter et al.[39]

Statistical analysis

All EMG data are reported as means and standard deviations (SD). To evaluate trunk muscle activity for the different squat types non-parametric one-way ANOVAs (Kruksal-Wallis) were separately calculated for each muscle and a pairwise comparison was conducted with the type of squat as a grouping variable. To report effect sizes, Hedges' g for small samples was calculated. A small effect was considered > 0.2, a medium effect >0.5 and a large effect > 0.8. To evaluate differences between trunk muscle activity in normal standing and standing only on the forefoot, a Wilcoxon test was applied for each type of squat in each phase, and also paired Hedges' g were calculated. For CoP path length a two (standing condition: normal, forefoot) x 3 (type of squat: back, front, overhead) repeated measures ANOVA was calculated and a post hoc (Tukey) to compare the type of squat was tested. In the same way, spine angle was tested.[25]

FIGURE 1. The figure showing representative data for a sequence of four back squats (BS) in the normal standing condition. With 'A' describing the vertical velocity of the trunk and 'B' the vertical displacement of the hip marker. EMG non-normalised raw data are displayed in panels 'C' (external oblique, EO), 'D'(internal oblique, IO), 'E' (rectus abdominis, RA), and 'F' (erector spinae, ES). 'G' and 'H' reveal the displacement of the center of pressure (CoP) in the anterior-posterior (AP) and medio-lateral (ML) directions, respectively.



RESULTS

Muscle activity

Trunk muscle activity is presented as means and SD in percent MVIC during three different phases of squatting (lowering, turning, raising) and for the total movement, for all muscles (EO, IO, RA and ES) in normal and reduced base of support (forefoot) standing conditions in Table 1. The greatest differences in muscle activity between the three types of squats were found for EO ($\chi^2(5)=15.4$, $p=.009$), with increasing muscle activity regarding the type of squat respectively (BS<FS<OS; Figure 2A). A medium effect in EO was observed during lowering and at the turning point for the FS (0.67<Hedges' g<0.74) and a large effect for OS in all phases for both normal and forefoot execution (1.05<g<1.24). Differences in muscle activity were also observed between the three types of squats for ES ($\chi^2(5)=12.2$, $p=0.03$; Figure 2D) and RA ($\chi^2(5)=14.4$, $p=0.013$; Figure 2C). In ES increasing muscle activity regarding the type of squat (BS<FS<OS) revealed in large effects during the lowering and the turning phases (0.84<g<0.1.49) and additionally medium effects for the raising phase in both standing conditions (0.51<g<0.74). Results for post-hoc tests also presented in Table 1. For IO and RA, only small effects were detected in muscle activity between the types of squats in any of the movement sequences (0.01<g<0.35). No significant difference in muscle activity was found for any muscle between the normal and reduced base of support, forefoot, standing (-0.16<g<0.29), except for the start and end phases for ES in the FS (0.49<g<0.63).

FIGURE 2. Group mean (solid line) and standard error of the mean (dotted line, only lower bound) for the MVIC normalized muscle activity of the four trunk muscles over the entire squat movement for the normal standing condition. The different colours represent the three squat types: OS (blue) FS (green) and BS (red). Note the different y-axis scale for each muscle.

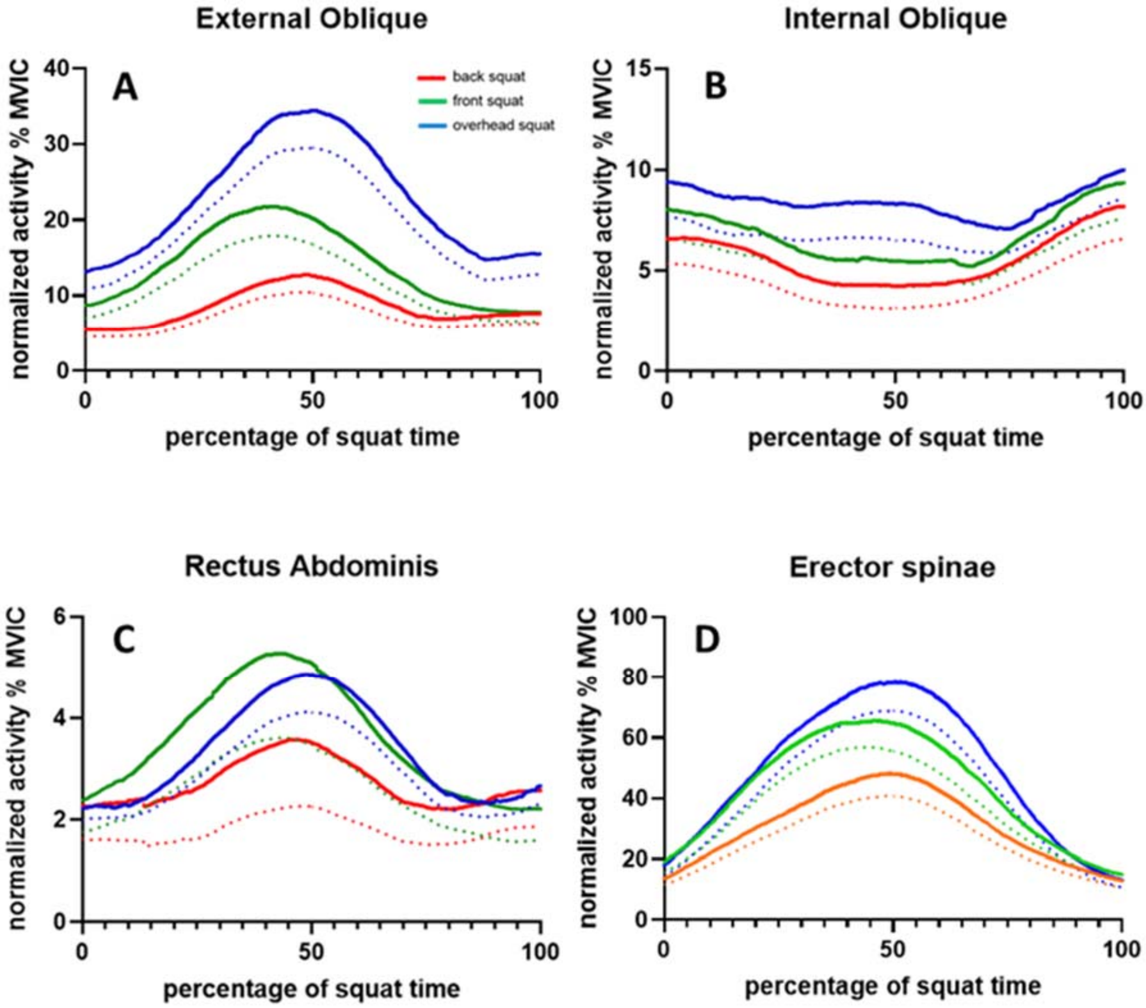


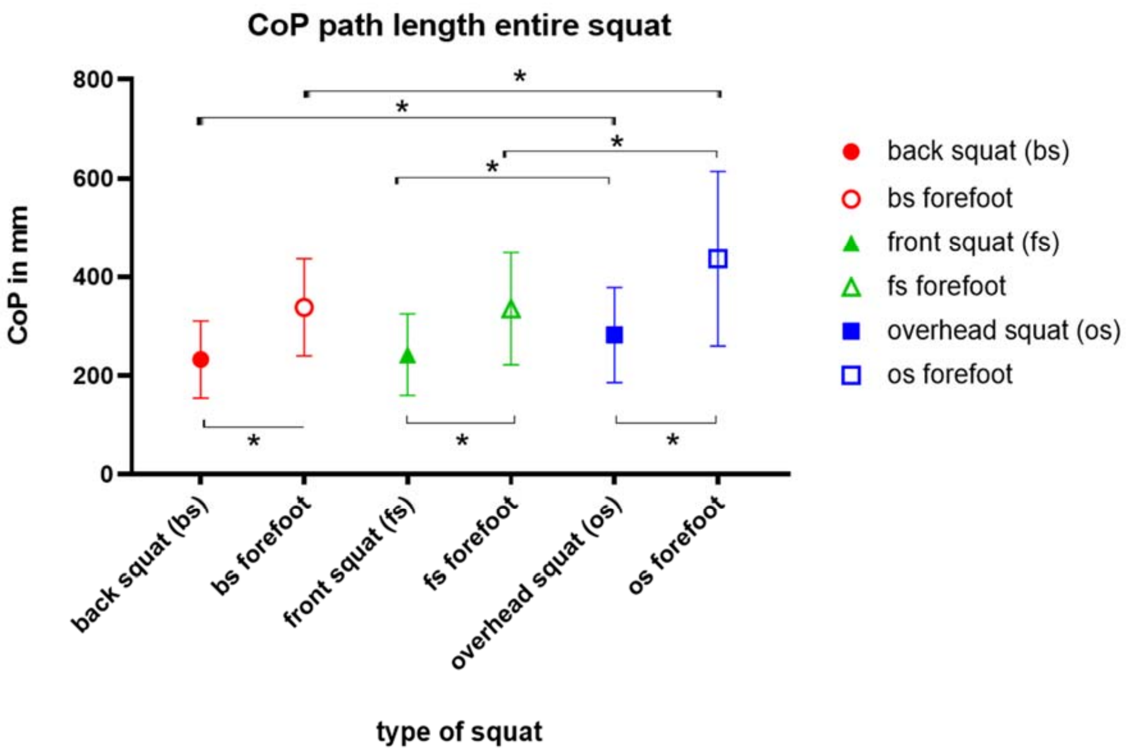
TABLE 1. Group mean and (SD) for the MVIC normalised EMG data during lowering, turning and raising phases for each squat condition, as well as for the complete squat. Annotation marks indicate differences between the back and front squat (*), back and overhead squat (*) and front and overhead squat (†) (p<0.05).

		Normal			Forefoot (reduced base of support)		
		Back Squat	Front Squat	Overhead Squat	Back Squat	Front Squat	Overhead Squat
% MVIC	Complete squat						
	EO	9.7 (5.2)	18.2* (9.6)	29.5*† (14.2)	9.9 (4.0)	16.8* (8.3)	26.7*† (13.3)
	IO	5.3 (3.7)	6.3* (4.0)	8.2*† (5.6)	5.5 (3.4)	6.3 (3.6)	8.3 (5.3)
	RA	3.0 (3.5)	4.2 (4.2)	7.3*† (5.2)	5.6 (3.6)	7.0 (5.6)	5.6 (4.5)
	ES	36.7 (17.4)	54.8* (28.1)	62.8*† (28.1)	43.5 (16.2)	55.9 (27.1)	60.6* (25.0)
	Lowering						
	EO	10.1 (4.5)	20.9* (8.6)	31.7*† (9.6)	10.1 (4.4)	20.2* (11.3)	28.6*† (13.9)
	IO	6.5 (5.2)	8.3 (5.1)	10.2* (6.9)	5.4 (4.1)	6.7 (4.9)	9.8* (6.8)
	RA	2.3 (0.8)	3.8* (1.4)	4.7* (1.4)	3.5 (3.9)	5.8 (6.4)	5.4 (5.0)
	ES	45 (20.8)	66.0* (30.3)	76.1* (30.8)	42.9 (16.6)	60.3* (31.6)	69.5* (34.3)
	Turning						
	EO	12.7 (6.8)	21.5* (9.3)	36.8*† (12.7)	10.8 (5.1)	20.2* (10.9)	32.3*† (15.5)
	IO	5 (3.7)	6.4 (4.0)	9.3* (5.9)	4.6 (3.8)	5.3 (4.3)	8.3* (6.1)
	RA	2.6 (0.9)	4.0* (1.5)	5.4*† (1.6)	3.2 (3.7)	5.0 (6.1)	6.0 (5.5)
	ES	54.3 (23.3)	74.2* (32)	88.5*† (36)	48.1 (16.2)	62.5 (26.8)	70.4* (29.7)
	Raising						
	EO	8.5 (5.2)	11.6 (5.6)	19.4*† (6.6)	7.4 (3.9)	10.2 (5.4)	18.3* (9.9)
	IO	5.9 (4.2)	7.0 (4.0)	8.2 (3.9)	6.0 (3.7)	6.5 (4)	8.9 (4.6)
	RA	2.1 (1.1)	2.5 (0.8)	3.2 (0.9)	8.1 (19)	6.2 (11.1)	4.8 (3.7)
	ES	31.2 (12.4)	39.5 (15.7)	41.4 (18.7)	36.0 (24.7)	38.6 (18.5)	35 (15.3)

CoP path length

The ANOVA for standing condition (normal vs forefoot) and type of squat (BS, FS, OS) revealed a difference in CoP path length ($F(2,22)=7.14$, $p=0.004$, $\eta^2=0.06$). Differences in the squat condition with respectively increasing path length of CoP were found post hoc between BS and OS (p=0.005) and BS_forefoot and OS_forefoot (p=0.002) as well as FS and OS (p=0.023) and FS_forefoot and OS_forefoot (p=0.002) (Figure 3). Differences were also observed between normal standing and standing on forefoot for all types BS (p=0.015, Hedges' g=1.15), FS (p=0.05, g=0.91) and OS (p=0.02, g=1.05).

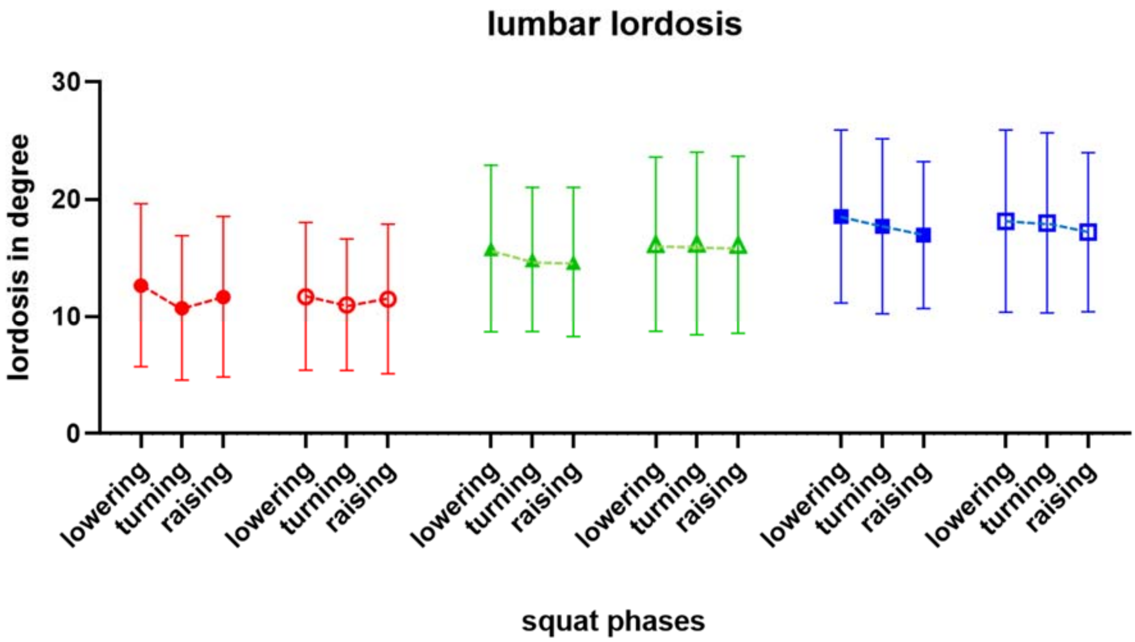
FIGURE 3. Mean centre of pressure (CoP) path length with SD for each type of squat (BS, back squat; FS, front squat; OS, overhead squat) for both standing conditions: normal and forefoot. * Statistically significant difference.



Spine curvature

The ANOVA for standing condition and type of squat revealed no significant difference in spine curvature ($F(2,108)=2.57$, $p=0.08$, $\eta^2=0.00$). Albeit differences with great effect sizes occurred between the types of squat: BS versus FS ($p<.001$; Hedges' $g=0.752$; [95.0%CI 0.39, 1.13]) and BS and OS ($p<.001$; $g=0.775$ [95.0%CI 0.392, 1.16]. The same occurred for forefoot standing, BS_forefoot and FS_forefoot ($p<.001$; $g=0.611$ [95.0%CI 0.245, 0.974] and BS_forefoot and OS_forefoot ($p<.001$; $g=0.677$ [95.0%CI 0.308, 1.04]. Generally, greater spinal curvature was observed in FS and OS compared to BS (Figure 4).

FIGURE 4. Spinal curvature as measured between Th12 – L2 – L4 for all squat conditions (red circles BS, green triangles FS, blue squares OS) in normal (filled) and forefoot (open) standing during different phases.



DISCUSSION

Strength exercises performed in ways that are similar to everyday life, or are sports specific, are considered optimal for strength training and rehabilitation. Aspects of the squat mimic movements that occur in daily life and are fundamental for many sports. As the focus of previous studies has been primarily assessing the activity of leg muscles when performing squats, the current study aimed to evaluate ventral and dorsal trunk muscle activity when performing the most common squatting exercises. The main finding of the study was that the position of the load (barbell) had the greatest effect on trunk muscle activity, with the magnitude increasing for all muscles as the load moved from the shoulders, to the front of the trunk and finally overhead. The greatest activity was always observed during the turning phase at the bottom of the movement, followed by the lowering then raising phases, in that order. Less obvious was any change in the magnitude of trunk muscle activity related to performing each of the three types of squat from an unstable position. While spinal curvature (lumbar lordosis) was not influenced by stability, there was an effect with squat type, with increased spinal curvature occurring when performing the front and overhead squats.

Trunk muscle activity and type of squats

Training conditions for trunk stability are considered optimal when performed close to being task- or sport-specific[8]. As such, different forms of squat exercises that challenge both leg strength and trunk stability, and can serve as suitable training exercises. When performed squats with a reduced base of support, by standing only on the balls of the feet, the task requirements may more closely represent changes in leg and trunk control that occur during dynamic activities such as jumping, landing, cutting, and running. However, the present study revealed no major differences in trunk muscle activation when performing the three types of squats from an unstable position, which was shown to be more challenging for balance by the increased total path length of each subject’s centre of pressure. What we did find, however, was that when performing the squats, the ventral trunk muscles, OE, and the primary back extensor, ES were the two most activated trunk muscles, relative to their recoded maximum. That finding is similar to that of Nesser et al.[28] who also investigated trunk muscle activity during squatting in trained and former athletes, but with significantly heavier loads i.e., 100% of body weight for the back squat and 75% of body weight for the front squat. One of the major functions of the back extensors is controlling the combined mass of the upper body via the production of a trunk extensor moment.[17] This is particularly the case when there is a large trunk flexion moment to overcome as the trunk is flexed forward and when additional anterior loads also increase this moment. Therefore, when performing squat exercises, an altered upper body position by leaning or flexing forward requires additional trunk extensor muscle activity to counteract the larger flexor moment. This explains the increase in ES activity when the barbell was moved anterior from the shoulders to the torso and finally overhead, which additionally raised the centre of mass, thereby increasing the body's toppling moment.

Of the abdominal muscles, EO was the ventral abdominal muscle that had the greatest level of activity compared to its recorded maximum, and the ventral muscle that had the greatest change in muscle activity across the different squat tasks. This is a similar finding to Andersen et al. [2] for performing Bulgarian squats, while Oshikawa et al.[30] found both EO and IO to have similar activation levels when performing 80% of a one-repetition maximum (1RM) squats to a position where the thighs were horizontal and 60% of 1RM for full squats. Despite this slight variation between studies, the oblique abdominal muscles do engage when there is a need to stabilize the trunk during this type of exercise. While producing a flexor trunk moment may seem counterproductive, the overall effect of their activation in concert with the trunk extensor muscles is likely to stiffen the trunk and its constituent spinal segments.[15,16,21,35] For EO, a possible explanation may be the first diagonal, afterwards vertical muscle fiber orientation of the muscle in combination with its location as the top layer, originating from the thorax as high as the 5th rib.[23] EO has a favourable lever for force generation to co-contract in counterbalance with the back extensor muscles in order to meet the requirements for stiffening the spinal column, especially when it comes to a squatting position.

In this study, the largest muscle activity was found during the turning and lowering phases of each squat. In contrast, Nesser et al.[28] and Anderson at al.[5] reported the highest activity of the trunk muscles during the upward phase. However, in both studies the movement was separated into only two phases, upward and lowering, while in our study, three phases were defined, including the turning point, which would overlap with the two phases of the other studies.[5,28] More comparable perhaps is the study by Oshikawa et al.[30] where the squat movement was divided into four phases, and where the highest muscle activity was found to occur in the early part of the upward movement as well as the late part of the lowering phase, which corresponds to the turning phase in this study.

The IO showed only a low level of activity and a relatively small change in amplitude during the different phases of both the balanced and reduced base of support trials, which is in line with the data of Nesser et al.[28] As IO usually contracts synergistically with transversus abdominis (TrA) during lifting, the activity of the IO, even though low, could potentially indicate activation of TrA during the squat task.[29] IO along with TrA are often characterized as muscles that stabilize the spine due to their fiber orientation, but have little impact on producing a trunk flexor moment.[15]

For RA small changes in muscle activity were only found for the reduced base of support condition. This is likely due to the fact that a large trunk flexor moment is not required when performing a squat. This is supported by the Behm et al.[11] who concluded that RA is more responsible for producing trunk flexion and less for stabilizing the spine.

As expected, the total CoP path length increased when performing squats from a more unstable position (a reduced based of support) which suggests that squatting tasks performed that way are more challenging, at least for balance. But surprisingly, this increase in task difficulty did not relate to a significant increase in trunk muscles activity. The study by Anderson et al.[2] also found no differences in EO and RA muscle activity when performing back squats while standing on foam cushion, compared to a solid surface. This appears to be also the case for leg muscles, as a study by Aranda et al.[6] found no differences in leg muscle EMG activity when performing squats on a stable or unstable surface. However, for a different form of exercise, side-planks performed on a Swiss Ball [15], greater activity of the lower-abdominals was found for the unstable condition. It therefore seems that any adaptations evoked by performing squats from an unstable position are non-existent or at least hard to detect.

Spinal curvature, as measured by skin markers placed over specific anatomical landmarks, showed expected movement patterns during the different types of squats, independent of whether they were performed on a stable or reduced base of support. All subjects had what would be considered a ‘normal’ lordosis, and this angle changed little during the back squat. When the load was moved anteriorly for performing the front squat, subject’s started with a slightly more pronounced lordosis, which lessened during the downward phase to the turning point. Interestingly, for the overhead squat, the lordosis at the start of the movement was similar to that of the FS, however in contrast to the FS and BS the lordosis angle increased during the downward phase. It should be noted that there was considerable difference in individual lordoses,[30] and some individual differences in lumbar spine curvature were observed between the back and two other squat types. Therefore, the type of squat seems to influence the extent of lumbar lordosis in novices.

Limitations

A methodological limitation can be seen in the reliable measurement of IO as this muscle is not easy to measure accurately. As another limitation, transverse abdominis, as one of four abdominals, was not directly measured, the activity of the muscle was only recorded in a surrogate measurement using IO. Also, to be mentioned, that despite ES and RA are big (long) muscles with potential regional differences in activity, we measured them only at one location. Further, the measurement of lumbar spine curvature with skin markers has its limitations due to the different position and movement of the skin and the joint depicted. Besides, no attention was paid to measure muscle activity of the involved leg muscles, but hip extensors like hamstring and gluteus muscles can influence the position of the pelvis and, therefore, indirectly the position of the lumbar lordosis. Therefore, future studies may take these factors into account.

CONCLUSION

Trunk muscle activity is altered by performing different types of squat exercises. EO and ES appear to be the trunk muscles most engaged when novices perform squat exercises with a modest load. Although performing squats from a reduced base of support resulted in greater overall instability, trunk muscle activity did not significantly increase. The lumbar spine angle can be affected by the type of squat exercise, although there were considerable inter-individual differences. Squat exercises are useful exercise for engaging specific trunk muscles and can be used for both athletic and rehabilitation populations. Performing squats in an unstable position does not appear to increase trunk muscle activation, although it may provide other benefits not measured here.

KEY POINTS

- **FINDINGS:** The type of squat exercise rather than a forefoot standing condition increases trunk muscle activity, whereas highest muscle activity is reached especially during the lowering phase and at the turning point.
- **IMPLICATIONS:** Low loaded squat exercises increase trunk muscle activity mainly in external oblique and erector spinae muscle. Therefore, squatting exercises can provide a way to activate the trunk muscles in a specific but common performance setting.
- **CAUTION:** Participants of this study were healthy people without back pain, and the results are not proofed to be entirely applicable to the setting of rehabilitation.

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Conclusion and Outlook

Conclusion

The emphasis of this PhD-project was based on understanding how to best determine the strength of the trunk muscles and whether the influence of trunk strength to athletic performance can be classified. The results of the three publications [1-3] and the submitted manuscript [4] are summarized and the main messages for the evaluation of trunk strength and its possible impact on sports performance highlighted.

Trunk strength assessments

Generally, the assessment of trunk strength can be rated as problematic and inconsistent. In this context, three aspects are worthy of being pointed out:

(I) With regard to reliability, findings of many studies as well as the own research show a high reliability of assessments targeting trunk strength. Thus, regardless of the assessment being highly reliable, concerns regarding the validity of trunk muscle strength assessments need to be considered nonetheless. In the course of this study, it became increasingly evident that little attention is placed on possible shortcomings in a differentiated measurement of trunk strength.

In this respect (II), the decision on what kind of trunk strength test is chosen rarely is a deliberate one. In fact, most studies use trunk strength endurance tests for quantifying trunk strength ability because they are simple, widely available, and commonly used. However, in the study about trunk strength in soccer players presented above, it became clear that strength endurance capacity was not comparable to maximal isometric strength outcome in high-level female and male players. Therefore, at least two kinds of strength abilities should fundamentally be determined; strength endurance and maximal strength output. The investigation of further strength abilities, i.e. the rate of force or torque development, could provide further insight into the strength abilities of trunk muscles. What remains noteworthy concerning trunk strength assessment in comparison with limb strength tests is the test protocol. The majority of strength tests for limb muscles apply a maximum strength test, either as a 1 RM or maximum isometric strength. These measurements reflect maximal athletic performance. Therefore, as mentioned by Wirth et al.[11], other strength abilities, in addition to endurance strength, should be measured in trunk muscles too.

(III) Moreover, the extent to which the trunk muscles contribute to the result of a trunk strength assessment is not sufficiently determined. Extremity muscles can potentially contribute to strength performance outcomes of the trunk. During the studies on this thesis, the question arose to what extent the limb muscles contribute to performance if the trunk muscle strength is actually to be evaluated in isolation. As shown the frequently used prone plank test is strongly influenced by the strength of the limbs, especially the arm muscles. It is interesting to note that the question of what level of strength of the extremities exactly affects these results is not a topic of discussion in the literature. This assumption is confirmed by looking at a current validation study of the prone plank test for the estimate of trunk strength. Blaisier et al.[7] do not address the contribution or bias of the extremity muscles at all, only hip flexors and back muscles are taken into account. Also, considerations to standardize the assessment position to minimize evasive movements (of the limbs) are rated only on a subjective basis. The validity of this method as a determination of abdominal and trunk muscle strength, thus, should be questioned and re-addressed. At best, it might be stated that this assumption it is not conclusively validated there. Functional anatomical relationships should be examined more closely and any muscles that may contribute to performance should also be examined and measured. This may help to better understand the sophisticated working unit of the trunk and to substantiate any conclusion in a more solid manner.

Muscle activity

Observation of muscle activity with EMG is regularly used to determine if and how much a defined muscle contributes to a movement. Two fields are commonly observed for muscle activity and were examined in this thesis. First, typical tasks of daily-, or sports activities and, secondly, specifically chosen strength exercises for trunk muscles. With reference to strengthening exercises it appeared that the involved muscles and the height of muscle activity serve as essential determinants. Study 1 shows high muscle activity during strengthening exercises such as the prone plank position. The activity of the abdominals exceeded 100% compared to a maximal normalization procedure (MVIC), depending on the duration of the exercise. Likewise, Behm et al.[4] listed a high activation for the lower abdominals in a side bridge position. Usually, the activity of the back muscles in these exercises is rather low due to the typical muscle activation in a bridging exercise. The benefit out of this kind of exercise is a particularly high activity of the targeted muscles.

In contrast, the analyzed squat movement represents a daily or athletic movement. As previously mentioned, the level of activity as well as the interaction of muscles here are of higher interest in this respect. Study 4, which analyzed core muscle activity during different squatting movements, showed that the external oblique (up to 36% MVIC) and the erector spinae (up to 88% MVIC) were the muscles with the highest activation. In an upright position, the back musculature has the task of creating the necessary torque to erect the spine. At the same time, but to a lower extent, the abdominals are also active in stabilizing the spine with a co-contraction but without creating a flexing moment. Loading and squat type can change the activity of the muscles, yet with the back muscles always showing highest activity.

Exercises targeting the abdominals specifically can produce higher activity than motions applied in everyday movements. This is comparable to strength exercises in the open kinetic chain for the extremities. In comparison, the muscles in an upright position show a different weighting in activation as described above. Similarly, this can be found in the extremities when movements are performed in a closed kinetic chain. The overall effect of the activation of the abdominals in concert with the trunk extensor muscles is likely to stiffen the trunk and its constituent spinal segments. These effects on the activation of the trunk musculature demonstrate that targeted strengthening exercises, compared to functional movements, activate the muscles in a different pattern. The conclusions to which extent this could potentially influence sport or therapy remains to be elucidated.

Athletic performance and trunk strength

Some studies have already attempted to demonstrate the impact of trunk muscle strength on the outcome of motor performance. As discussed above, the strength tests for the trunk muscles were usually assessed by endurance test protocols. The question of the validity of these trunk strength tests should be re-considered again. Furthermore, athletic performance was recorded in the form of sprints, jumps, throws, and 1 RM tests. The results of the various studies generally showed weak to medium correlations between the results of measuring the strength of the abdominal or back muscles and athletic performance. In a meta-analysis on this topic, the authors[9] reached a similar conclusion after the evaluation of 31 included studies.

As greater muscle strength usually leads to higher performance the general assumption that trunk strength basically also influences motor performance is reasonable. In order to provide evidence for this assumption, we followed the approach of locally fatiguing muscles and measuring the effects on selected motor performance parameters. This approach seems especially reasonable and fitting for the leg muscles: fatigued quadriceps lead to less maximum strength which in turn lowers sprint performance. For the trunk muscles one can therefore expect the following model: fatigued trunk muscles leading to decreased strength, resulting in missing stability for limb movements, and in turn lowering sprint performance. The usefulness of this model seems to be that by measuring the muscle strength before and after the fatigue protocol the effects can be determined by looking at the level of strength loss. To sum up, these assessments allow for more general conclusions about the relevance of the fatigued muscles on motor performance parameters.

As another conclusion study 3 revealed that the strength of the trunk muscles has an essential influence on motor performance parameters. However, the fatigue of the leg muscles had a more considerable influence on parameters such as agility, straight sprint, and balance. The development of muscle strength in the lower extremities can, therefore, be regarded as the most crucial component of athletic training to improve sport performance. However, trunk strength training can be considered a relevant training supplement.

Methodological limitations

The study of the complex topic of trunk muscle strength provides for the use of many biomechanical assessment methods. The study design and measurement methods employed in this thesis were used to strengthen the conclusions made in the investigations conducted even though some methodological limitations need to be observed.

All studies investigated groups of young and healthy sports students or athletes. Therefore, the results are not necessarily transferable to other populations such as, for instance, rehab patients, elderly persons or children. These populations should also be assessed, separately.

With regard to strength assessment we evaluated peak torque, as this parameter is commonly used in the majority of studies in order to assess isometric or isokinetic strength. Further parameters like rate of torque development or the time series curve may also be relevant from a practical perspective and, thus, should additionally be included in future studies.

EMG assessment of trunk muscles is a complex matter as the muscle architecture of the trunk muscles is sophistically multi-layered. However, electrode placement in all tests was the same, applied by the same tester and following the widely acknowledged SENIAM guidelines. A filtering of the heartbeat[6] was not conducted as only the muscles of the right side of the trunk were analyzed. Unfortunately, from a test economic rationale not all muscles of interest have always been examined. Further muscular structures of research interest are the limb muscles during planking and hip extensors while squatting.

Study 4 used a kinematic system to track lumbar spine curvature with skin markers placed over the lumbar spinous process. Though the method was validated, it has its limitations due to the different position and movement of the skin and the joint depicted.

Finally, the multifaceted functional anatomical interaction of the trunk muscles described in the anatomy section must be considered in conjunction with the muscles that directly or indirectly influence the spinal column. Muscles such as iliopsoas or latissimus dorsi have a direct influence; muscles such as glutes, hamstrings and adductors have an indirect influence. Therefore, as has been pointed out before, isolated fatiguing of a particular muscle group seems hardly possible when movements have a functional component. Conversely, this also shows the difficulty of testing the trunk muscles in isolation, no matter whether it is abdominal or back muscles. In study 4 we also disregarded the measurement of the contribution of the leg muscles involved. As hip extensors like hamstrings and gluteus muscles largely influence the position of the pelvis and, therefore, indirectly the position of the lumbar lordosis, this aspect should be taken into account in future studies.

Outlook

In response to the guiding research question, further approaches came into focus which could promote the understanding of the interrelations in this field of work and could become a subject of further trunk performance research.

In study 3, the fatigue of the trunk muscles showed a reduction in performance, i.e. agility and balance. The review of Allum et al.[3] provides fascinating indications with a slightly different perspective. The trunk mechanoreceptors could provide an expanded pool of sensors to give information about the acceleration direction and force exerted from the upper body to the central nervous system. Hence, the contribution of the trunk musculature is not only due to the presented strength performance, but also to the proprioceptive capacity of the trunk muscles which should be another topic in future studies.

Based on a task-specific training approach the targeted training should use the trunk strength exercises while standing to enable a more direct applicability than such exercises while lying or sitting. Again, the benefits from this approach could be the subject of future research.

Moreover, from an anatomical point of view, the origin of the dorsal chain of hip muscles in the fascia thoracolumbalis[2], the starting point of the trunk muscles, suggests that there is a structural connection between the trunk and the lower limbs. Therefore, if one were to consider these aspects in balance and stability training, exercises that simultaneously involve the trunk and the lower limbs appear to be offer promising results. Again, exercises in a standing position open up a supplementary spectrum[1], as long as proper coordinative execution is applied. Finally, trunk strength tests are rarely applied in a standing position.[5] Most of the applied tests take place in a lying, prone, or supine position.[8] These testing settings very rarely correspond to everyday movements or demands in sport.

In summing up the discussion it might be noted that to balance a stick on the palm by moving the hand seems less exhausting than to grasp the stick and to fix it in the vertical position. Strength of the trunk muscles (and the hip) is necessary primarily to work against gravity to keep the trunk and spine stable or to bring it back into a stable position (to prevent tilting and buckling). For functional abdominal muscle training this means that a differentiated (task-orientated, functional) training with economic use of strength at the right moment is more important than lifting the stretched legs from supine position.[10] Change of direction as well as stop and go tasks could be exercises for practical application. Coordinated and well-mobile hip joints with well-functioning muscles should facilitate the task. Besides the required trunk muscles needed in this combination neighbored and functional connected muscle like those of the hip need to be activated. Further research can target these assumptions by understanding or creating the right exercises for better sports performance and injury prevention.

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Figures and Tables

Introduction

Publication 1: Muscle activation and performance during trunk strength testing in high-level female and male football players

Publication 2: Absolute and relative reliability of isokinetic and isometric trunk strength testing using the IsoMed-2000 dynamometer

Figure 1: Positioning for the testing of trunk extension, flexion (A) as well as rotation (B) on the IsoMed 2000 device

Figure 2: Exemplary torque curve during one set of concentric flexion and extension at a speed of 60_/sec, black, unfiltered data, gray, filtered data.

Table 1: Average values and reliability data for isometric and isokinetic tasks (flexion/extension and left/right rotation) from familiarization day to day 1; Reliability data for the analysis of day 1 to day 4 only (p-value (ANOVA), SEM, CoV, and ICC with 90% CI, MDC).

Table 2: Absolute und relative reliability trunk strength PT/LBM in kg between familiarization day and day 1.

Table 3: Pearson Correlation Coefficient filtered to unfiltered peak torques in various tasks.

Publication 3: Acute leg and trunk muscle fatigue differentially affect strength, sprint, agility, and balance in young adults

Figure 1: Procedure of the CH-cross test: numbers give the chronological moving sequence; dots represent the pylons marking the turning points, whereas the direction of movement is displayed in the figure.

Figure 2: Decline in performance during the fatigue protocols is displayed by the Russian twist (indicating acute trunk fatigue; repetitions/60 seconds) and by repeated countermovement jumping (CMJ; indicating acute leg fatigue; total jump height in meters/45 seconds) over the course of 4 sets within 20 minutes.

Figure 3: Standardized mean differences (SMDs) with 90% CI and the probabilities of the differences showing negative, trivial, or positive effects of leg fatigue vs. control, trunk fatigue vs. control, and leg vs. trunk fatigue. CI = confidence interval.

Table 1: Absolute strength values (peak torque) and motor test results as means and SDs and p values for ANCOVA.

Table 2: Absolute mean and percentage differences with 90% CI of isokinetic strength and motor tests for leg fatigue vs. control, trunk fatigue vs. control, and leg vs. trunk fatigue.

Publication 4: Trunk muscle activity during different types of squatting under stable and unstable conditions in healthy young adults

Figure 1: The figure showing representative data for a sequence of four back squats (BS) in the normal standing condition. With 'A' describing the vertical velocity of the trunk and 'B' the vertical displacement of the hip marker. EMG non-normalized raw data are displayed in panels 'C' (external oblique, EO), 'D'(internal oblique, IO), 'E' (rectus abdominis, RA), and 'F' (erector spinae,

ES). 'G' and 'H' reveal the displacement of the center of pressure (CoP) in the anterior-posterior (AP) and medio-lateral (ML) directions, respectively.

Figure 2: Group mean (solid line) and standard error of the mean (dotted line, only lower bound) for the MVIC normalized muscle activity of the four trunk muscles over the entire squat movement for the normal standing condition. The different colors represent the three squat types: OS (blue) FS (green) and BS (red). Note the different y-axis scale for each muscle

Figure 3: Mean center of pressure (CoP) path length with SD for each type of squat (BS, back squat; FS, front squat; OS, overhead squat) for both standing conditions: normal and forefoot. * Statistically significant difference.

Figure 4: Spinal curvature as measured between Th12 – L2 – L4 for all squat conditions (circles BS, triangles FS, squares OS) in normal (filled) and forefoot (open) standing.

Table 1: Group mean and (SD) for the MVIC normalized EMG data during lowering, turning and raising phases for each squat condition, as well as for the complete squat. Annotation marks indicate differences between the back and front squat (*), back and overhead squat (*) and front and overhead squat (†) ($p<0.05$).

List of Abbreviations

1 RM	one repetition maximum
2-5 RM	two to five repetition maximum
cm	centimeter
COD	change of direction
Con	concentric
CoV	coefficient of variation
Ecc	eccentric
EO	external oblique
ES	erector spinae
ICC	intraclass correlation coefficient
IO	internal oblique
m	meter
N	Newton
Nm	Newton*meter (torque)
r	correlation coefficient r
RA	rectus abdominis
RFD	rate of force development
RTD	rate of torque development
s	seconds
SEM	standard error of measurement
TMS	Trunk Muscle Strength

Contributions

The topic of this work has emerged from my practical experience in rehabilitation and prevention. My motivation was and still is to understand the trunk system better. The author of this dissertation was in the lead of the development of the project ideas, the elaboration of the questions, ethics proposals, study executions, data evaluations and the preparation of the manuscript drafts. In order to ensure the best possible result, the contents of the publications were further developed in an interdisciplinary team. Although the main work was conducted by the author of this thesis (RR), four experienced scientists have made valuable contributions, namely, PD Dr. Oliver Faude (OF), Prof. Dr. Lars Donath (LD), Prof. Dr. Andrew Cresswell (AC), Eduard Kurz (EK) and Prof. Dr. Lukas Zahner (LZ). In the following, the contributions of the authors are listed. The order of the authors is the same as in the published or submitted articles.

Publication 1: Muscle activation and performance during trunk strength testing in high-level female and male football players
LD: Suggestions for data interpretation, suggestions for graphical representation of figures, and critical reviewing of the manuscript for important intellectual content.
LZ: Critical reviewing of the manuscript.
OF: Suggestions for data interpretation, and critical reviewing of the manuscript for important intellectual content.

Publication 2: Absolute and relative reliability of isokinetic and isometric trunk strength testing using the IsoMed-2000 dynamometer
LD: Suggestions for data interpretation, suggestions for graphical representation of figures, and critical reviewing of the manuscript for important intellectual content.
EK: Assistance with processing of raw data, assistance with writing of the results.
LZ: Critical reviewing of the manuscript.
OF: Design of the study, suggestions for data interpretation, suggestions for graphical representation of figures, and critical reviewing of the manuscript for important intellectual content.

Publication 3: Acute leg and trunk muscle fatigue differentially affect strength, sprint, agility, and balance in young adults
LD: Suggestions for data interpretation, suggestions for graphical representation of figures, and critical reviewing of the manuscript for important intellectual content.
LZ: Critical reviewing of the manuscript.
OF: Design of the study, suggestions for data interpretation, suggestions for graphical representation of figures, and critical reviewing of the manuscript for important intellectual content.

Publication 4: Trunk muscle activity during different types of squatting under stable and unstable conditions in healthy young adults
OF: Suggestions for data interpretation, suggestions for graphical representation of figures, and critical reviewing of the manuscript for important intellectual content.
LD: Suggestions for data interpretation, and critical reviewing of the manuscript for important intellectual content.
AC: Design of the study, suggestions for data interpretation, suggestions for graphical representation of figures, and critical reviewing of the manuscript for important intellectual content.

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Academic Experience

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	Lecturer "Angewandte Bewegungstherapie" (Bachelor level)
	Lecturer "Trainingsplanung, -durchführung und -auswertung" (Bachelor level)
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Awards

2016	«Swiss Olympic Science Award», 2nd, Magglingen
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Publication List

Roth R, Donath L, Zahner L, Faude O. (2019) Acute Leg and Trunk Muscle Fatigue Differentially Affect Strength, Sprint, Agility, and Balance in Young Adults. *Journal of Strength and Conditioning Research.*

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Kriemler S, Puder J, Zahner L, **Roth R**, Meyer U, Bedogni G. (2010) Estimation of percentage body fat in 6- to 13-year-old children by skinfold thickness, body mass index and waist circumference. *The British Journal of Nutrition.*

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Moses S, Meyer U, Puder J, **Roth R**, Zahner L, Kriemler S. (2007) Das Bewegungsverhalten von Primarschulkindern in der Schweiz. *Schweizerische Zeitschrift für Sportmedizin und Sporttraumatologie.*

Zahner L, Puder J, **Roth R**, Schmid M, Guldimann R, Pühse U, Knöpfli M, Braun-Fahrländer C, Marti B, Kriemler S. (2006) A school-based physical activity program to improve health and fitness in children aged 6-13 years ("Kinder-Sportstudie KISS"): study design of a randomized controlled trial. *BMC Public Health.*

Reviewer Work

Reviewer for the Journal of Sports Science and Medicine

Reviewer for the Deutsche Zeitschrift für Sportmedizin

Reviewer for Physical Therapy in Sport

Reviewer for Journal of Sports Sciences: Science and Medicine in Football

Conference Participations

Roth R, Bernhard T, Spörri J, Franchi M, Kohler C, Zahner L, Faude O (2018, oral) "Strength development of hamstring and quadriceps muscles in high-level youth soccer players", Annual congress of the European College of Sport Science, Dublin

Roth R, Kurz E, Faude O, Zahner L, Donath L (2018, poster)" Leg and trunk muscle activity in different positions performing on a double slackline in young adults", Congress of the International Society of Electrophysiology and Kinesiology, Dublin

Roth R, Donath L, Faude O, Cresswell AG (2017, oral)" Trunk muscle activity and lumbar spine curvature during stable and unstable back, front and overhead squat",Schweizerische Gesellschaft für Sportwissenschaft (SGS), Magglingen

Roth R, Donath L, Betschart M, Zahner L, Faude O (2016, oral) "Strength and balance development during one competitive season in high level female football players" Annual congress of the European College of Sport Science, Wien

Roth R, Donath L, Betschart M, Zahner L, Faude O (2015, mini-oral) "Strength and balance development in female soccer players" Annual congress of the European College of Sport Science, Malmö

Roth R, Donath L, Lustenberger K, Furer T, Zahner L, Faude O (2015, oral) "Ermüdung von Bein- und Rumpfmuskulatur: Einfluss auf Kraft, Gleichgewicht und Sprintfähigkeit bei jungen sportlichen Erwachsenen", dvs-Tagung, Sektion Trainingswissenschaft, Potsdam

Roth R, Donath L, Lustenberger K, Furer T, Zahner L, Faude O (2015, oral) "Fatiguing lower limb and trunk musculature: impact on strength, balance and sprint ability in sportive young adults", Schweizerische Gesellschaft für Sportwissenschaft (SGS), Lausanne

Roth R, Müller J, Donath L, Cresswell AG (2014, oral) "Trunk muscle activity during different types of stable and unstable squatting", Congress of the International Society of Electrophysiology and Kinesiology, Rome

Roth R, Donath L, Breton P, Zahner L, Faude O (2014, poster) „Impact of a 6-week trunk stability training on balance performance and agility", XXIII International Conference of Sport Rehabilitation and Traumatology, Milano, Italy

Roth R, Donath L, Bosshard S, Zahner L, Faude O (2014, poster) „Are core strength and spine flexibility predictors of shoulder and back pain in adolescent volleyball players?", SGS, Fribourg

Roth R, Donath L, Faude, O, Ramp A, Schmidt-Trucksäss A, Cordes M (2013, poster) „Validity and reliability of a portable and a stationary dynamometer for measurement of isometric leg strength in healthy young men", SGS, Basel

Roth R, Di Giovine D, Donath L, Zahner L, Faude O (2013, poster) „Auswirkungen eines siebenwöchigen spezifischen Schnellkrafttrainings während der laufenden Saison auf verschiedene physische Leistungsparameter bei leistungssportlich aktiven Fußballspielern: eine kontrolliert randomisierte Studie", 2. DFB-Wissenschaftskongress, Frankfurt

Roth R, Breton P, Donath L, Zahner L, Faude O (2013, poster) „Auswirkungen eines 6-wöchigen spezifischen Rumpfkrafttrainings auf Gleichgewicht und Richtungswechselschnelligkeit", 24. Jahrestagung dvs-Komission Fussball, Weiler im Allgäu

Roth R, Donath L, Moersen N, Zahner L, Faude O (2012, poster) „Muskelaktivierung und Rumpfkraft im Spitzenfussball: Vergleich zwischen Labor- und Feldmessung", Deutscher Sportärztekongress, Berlin

Roth R, Donath L, Moersen N, Zahner L, Faude O (2012, poster) „A comparison of two different tests to assess core strength in athletes", SGS, Magglingen

Roth R (2011) Workshop: Gleichgewichtstraining – wann, wo, wie? Schweizer Sportmedizin Kongress, Lausanne

Roth R, Zahner L (2007) Gesunde Kindheit – aktives Leben. Vortrag, Schweizerische Gesellschaft für Ernährung, Bern

Graduate Education

Course

"Biostatistik I", led by Prof. Dr. Marc Zwahlen	3
Winter School 2014 Writing a Journal Article … and Getting it Published; Swiss School of Public Health, Kali Tal	1
Good Clinical Practice (GCP) Basiskurs, Clinical Trial Unit Basel	0
Good Clinical Practice (GCP) Sponsor-Investigator, Clinical Trial Unit Basel	0
"Seminar Statistik" , led by Dr.Juliane Schäfer / Dr. Lars Donath	4
"Project Management for Researcher", led by Dr. Dimitrije Krstic	1
"Behind the Scenes of Academic Publishing—A Publisher's Perspective" led by Franck Vazquez	-
„Mindful Career Planning" led by Anya Häusermann	1
„Research Integrity: Zitat, Paraphrase oder Plagiat?" led by Prof. Klaus-Peter Rippe	1
"Effizient recherchieren" led by Dr. Philipp Mayer	0
Systematic Reviews and Meta-Analysis: a practical Approach; Swiss School of Public Health, Matthias Egger	1
Medical Decision Making; University of Lucerne, Brendan Delaney, Olga Kostopoulou	1
Introduction to the statistical software R; Swiss School of Public Health, Jan Hattendorf	0